T2K Results

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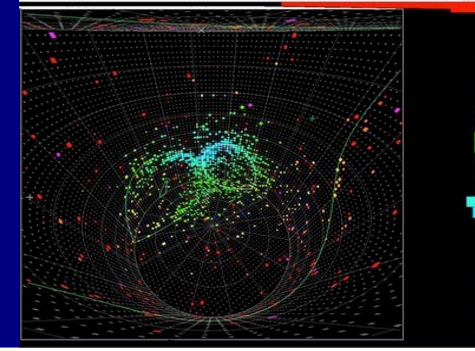
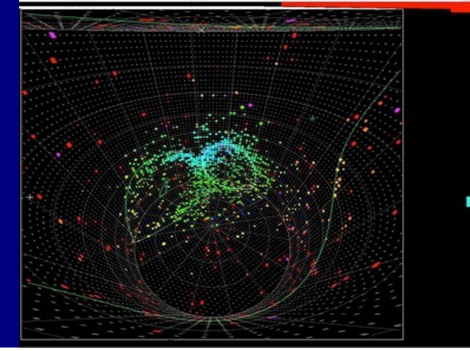
INFO2013

Overview



- Review of Neutrino Oscillations
- The T2K experiment
- Latest results
  - ν_e appearance measurement
  - ν_μ disappearance measurement
- What's next for T2K?
- Summary and Conclusion

Neutrino Mixing

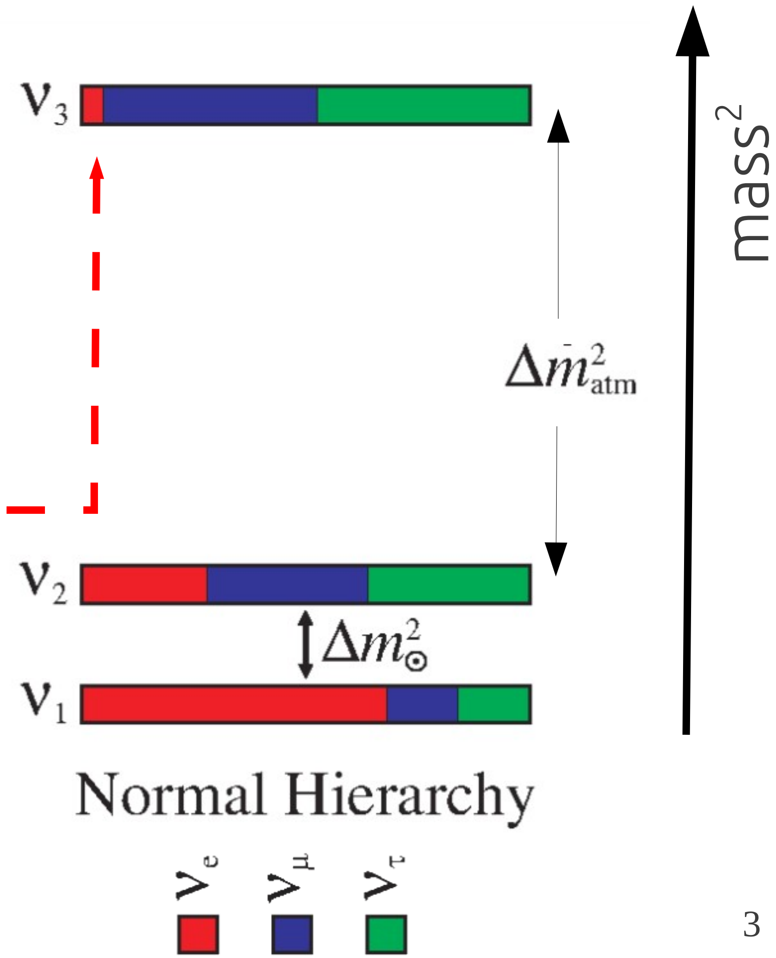


Neutrino flavour states are not the same as neutrino mass states

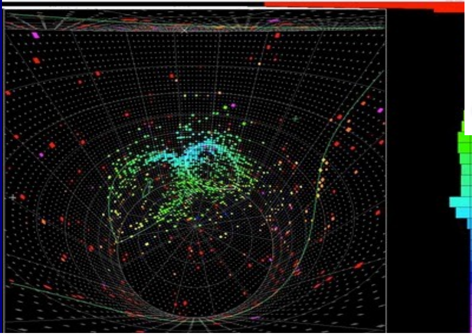
$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U_{\alpha i} |\nu_i\rangle$$

Oscillations parametrised by a complex 3x3 mixing matrix called the PMNS matrix.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 3} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



Oscillations : Current Status



$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\times\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13}\end{pmatrix}\times\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\times\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

$\nu_\mu \rightarrow \nu_\tau$

$$\sin^2 2\theta_{23} > 0.95 (@90\%)$$

$$\Delta m^2_{32} = (2.35 \pm 0.11)\times 10^{-3}\, eV^2$$

SK, MINOS, T2K, K2K

T2K,MINOS (App)
Daya Bay, RENO
Double CHOOZ (Dis)

$\nu_\mu \rightarrow \nu_e$

$$\sin^2(2\theta_{13}) = 0.098 \pm 0.013^*$$

$$\Delta m^2_{32} = (2.35 \pm 0.11)\times 10^{-3}\ eV^2$$

SK, SNO, Borexino
IceCube

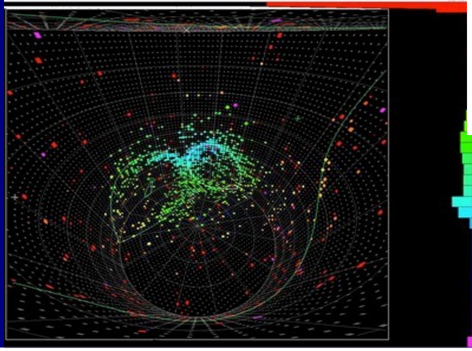
$\nu_e \rightarrow \nu_x$

$$\sin^2(\theta_{12}) = 0.306 \pm 0.018$$

$$\Delta m^2_{12} = (7.59 \pm 0.2)\times 10^{-5}\, eV^2$$

* Daya Bay
Other results from PDG(2012)

Two flavour oscillations



Appearance Measurement

Mixing angle Mass splitting Baseline

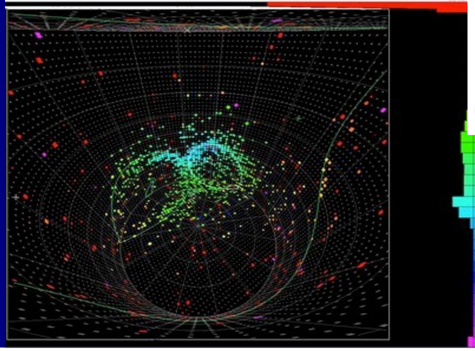
$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2(2\theta_{13})\sin^2(\theta_{23})\sin^2(1.27\Delta m^2_{13}\frac{L}{E})$$

+ CPV terms + subleading terms

Disappearance Measurement

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2(2\theta_{23})\sin^2(1.27\Delta m^2_{23}\frac{L}{E})$$

Three flavour oscillation ν_e appearance approx.



J. Arafune, M. Koike and J. Sato, Phys. Rev.D56, 3093 (1997).

Dominant vacuum term

$$P(\nu_\mu \rightarrow \nu_e) \approx 4 C_{13}^2 S_{13}^2 S_{23}^2 \sin\left(\frac{\Delta m_{31}^2 L}{4E}\right) \times \left(1 + \frac{2a}{\Delta m_{31}^2}(1 - 2 S_{13}^2)\right)$$

$$+8 C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cos\left(\frac{\Delta m_{32}^2 L}{4E}\right) \sin\left(\frac{\Delta m_{31}^2 L}{4E}\right) \sin\left(\frac{\Delta m_{21}^2 L}{4E}\right)$$

CP conserving term

$$-8 C_{13}^2 S_{13}^2 S_{23}^2 \cos\left(\frac{\Delta m_{32}^2 L}{4E}\right) \sin\left(\frac{\Delta m_{31}^2 L}{4E}\right) \frac{aL}{4E} (1 - 2 S_{13}^2)$$

Matter effect terms

$$-8 C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin\left(\frac{\Delta m_{32}^2 L}{4E}\right) \sin\left(\frac{\Delta m_{31}^2 L}{4E}\right) \sin\left(\frac{\Delta m_{21}^2 L}{4E}\right)$$

CP sinδ term

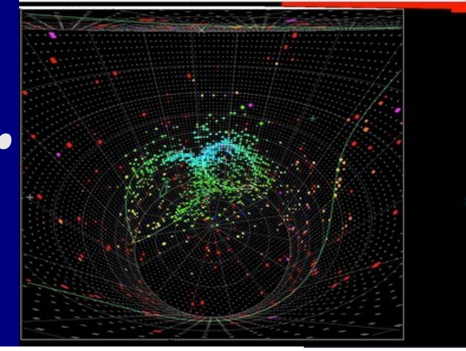
$$+4 S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2 C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta) \sin\left(\frac{\Delta m_{21}^2 L}{4E}\right)$$

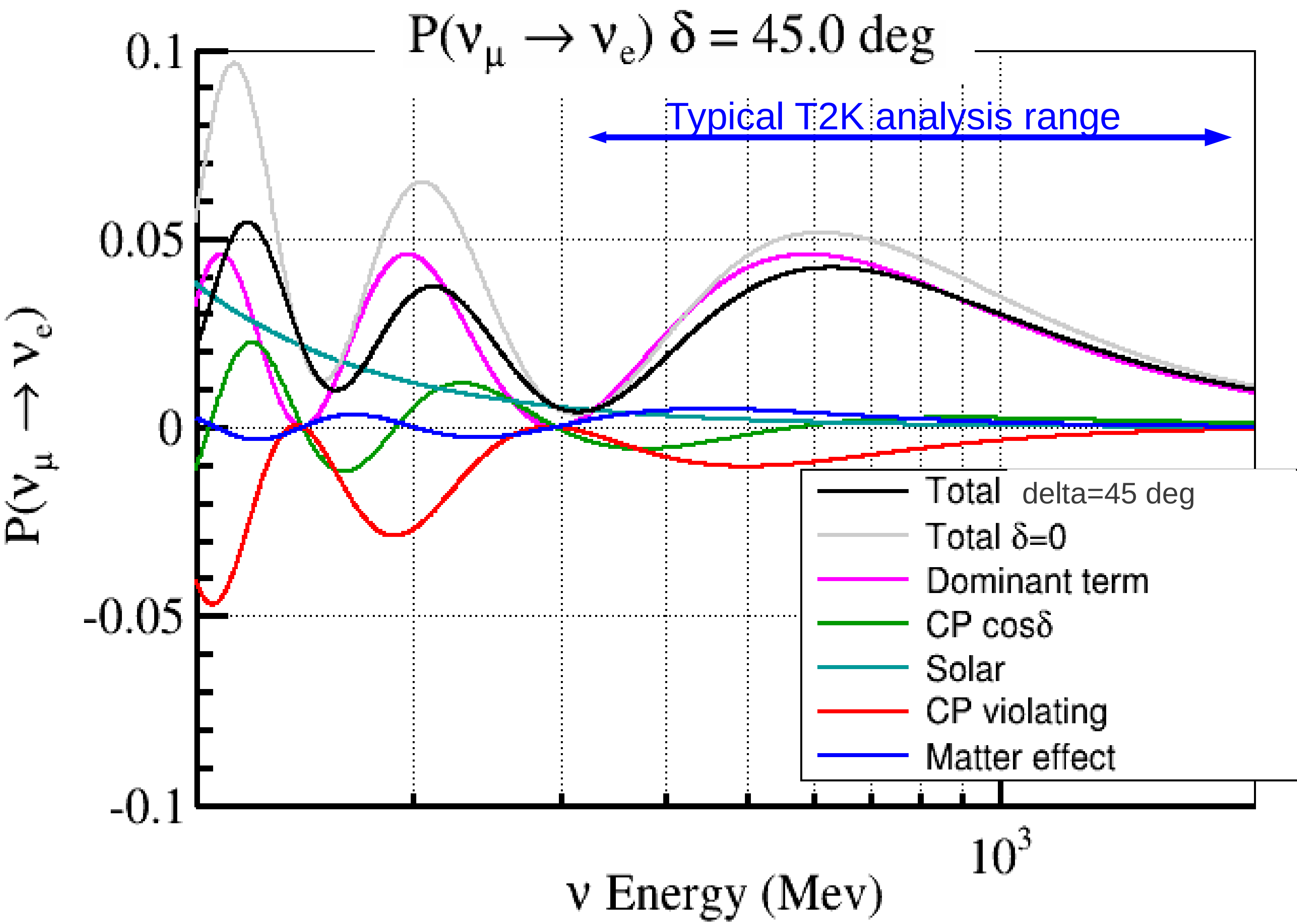
Solar term

Notes: Cij = cosθij, Sij = sinθij

$$a = 2\sqrt{2} G_F n_e E = 7.56 \times 10^{-5} \rho(g/cm^3) E(GeV)$$

3 flavour oscillation approx. w/ matter effects





Plot for:
L = 295 km
$\rho = 2.6\ g/cm^3$
$\Delta m_{12} = 7.6x10^5\ eV^2$
$\Delta m_{32} = 2.4x10^3\ eV^2$
$\theta_{12} = 34^\circ$
$\theta_{23} = 45^\circ$
$\theta_{13} = 8.8^\circ$
$\delta = 45^\circ$

nb. Same colour Scheme as Previous page

The T2K Collaboration

~ 500 members, 59 Institutes, 11 countries

Canada
TRIUMF
U. Alberta
U. B. C.
U. Regina
U. Toronto
U. Victoria
U. Winnipeg
York U.

France
CEA Saclay
IPN Lyon
LLR E. Poly.
LPNHE Paris

Germany
Aachen U.

Italy
INFN, U. Bari
INFN, U. Napoli
INFN, U. Padova
INFN, U. Roma

Japan
ICRR Kamioka
ICRR RCCN
Kavli IPMU
KEK
Kobe U.
Kyoto U.
Miyagi U. Edu.
Osaka City U.
Okayama U.
Tokyo Metro. U.
U. Tokyo

Poland
IFJ PAN, Cracow
NCBJ, Warsaw
U. Silesia, Katowice
U. Warsaw
Warsaw U. T.
Wroklaw U.

Russia
INR

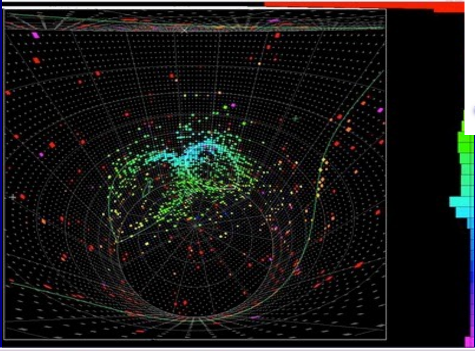
Spain
IFAE, Barcelona
IFIC, Valencia

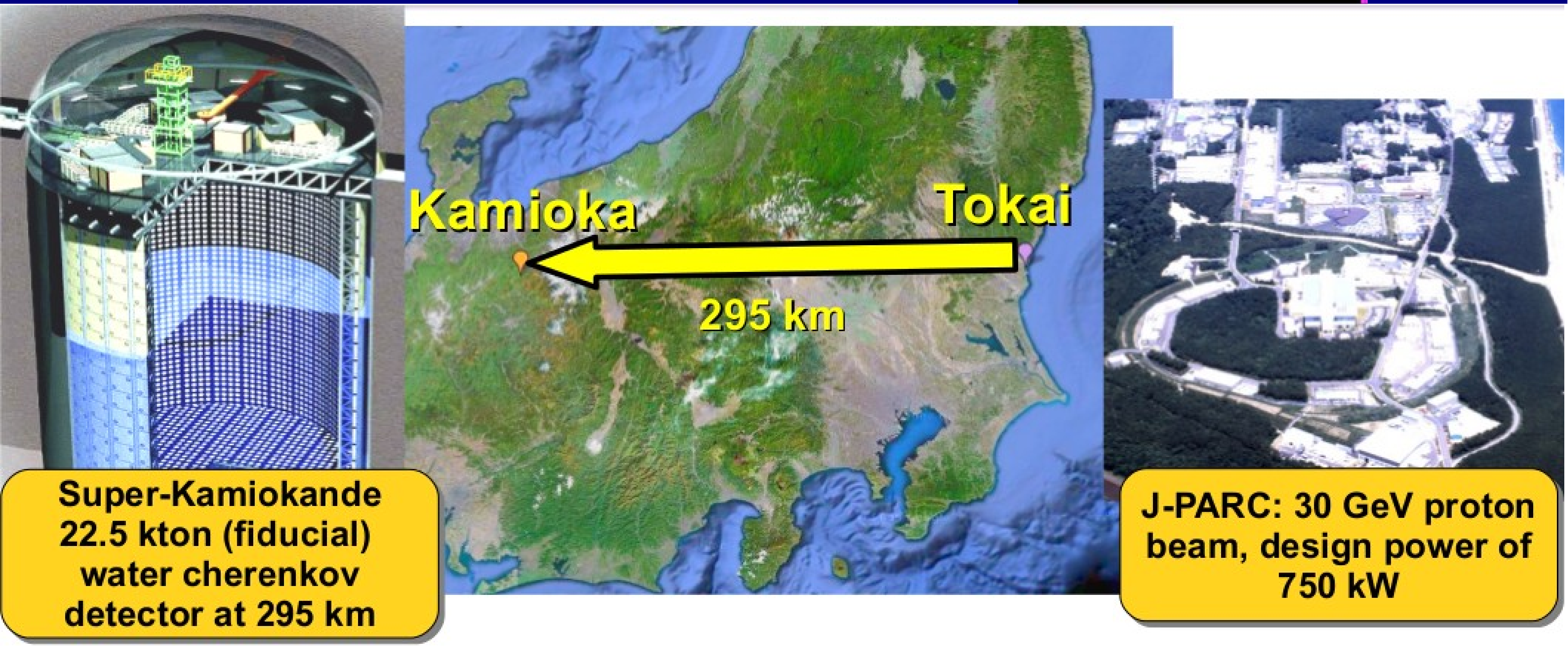
Switzerland
ETH Zurich
U. Bern
U. Geneva

United Kingdom
Imperial C. London
Lancaster U.
Oxford U.
Queen Mary U. L.
STFC/Daresbury
STFC/RAL
U. Liverpool
U. Sheffield
U. Warwick

USA
Boston U.
Colorado S. U.
Duke U.
Louisiana S. U.
Stony Brook U.
U. C. Irvine
U. Colorado
U. Pittsburgh
U. Rochester
U. Washington

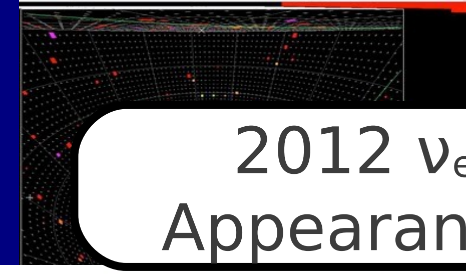
Overview of T2K



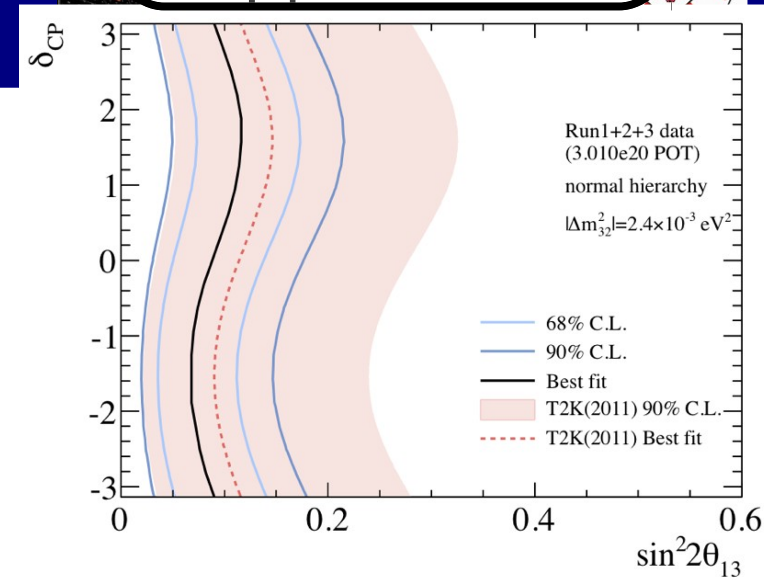


- Measure ν_e appearance in a ν_μ beam
- Precision measurement of ν_μ disappearance

Previous T2K Results

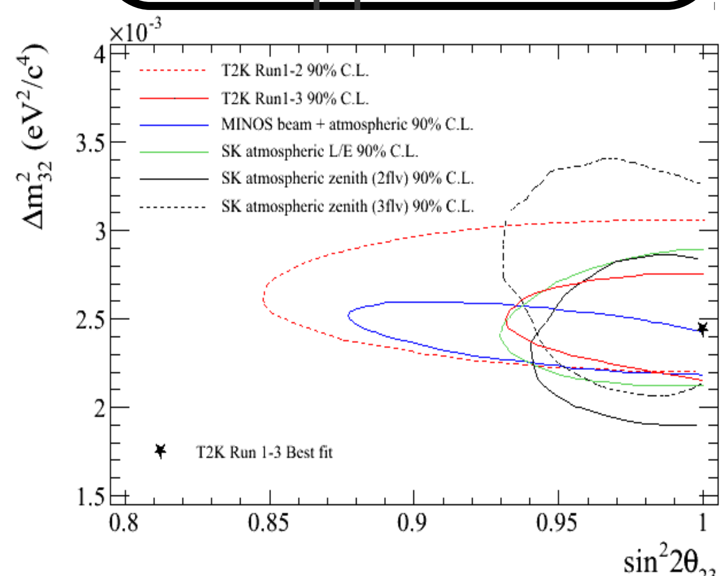


2012 ν_e Appearance

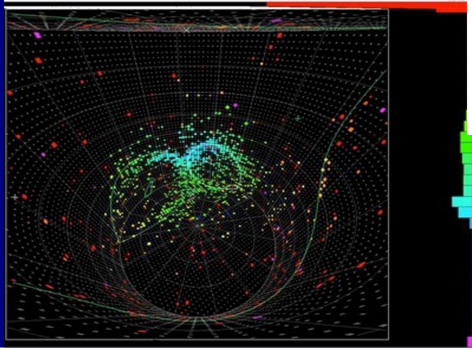


- **2011 ν_e appearance**
  - Observed 6 events (bg: 1.5 ± 0.3 events)
  - First indication of **non-zero θ_{13} at 2.5σ** significance
  - Phys. Rev. Lett. 107, 041801 (2011)
- **2012 ν_e appearance**
  - Observed 11 events (background: 3.3 ± 0.4 events)
- **3.1σ non-zero θ_{13}**
  - Phys. Rev. D88, 032002 (2013)
- **2013 ν_μ disappearance**
  - Phys. Rev. D87, 092003 (2013)

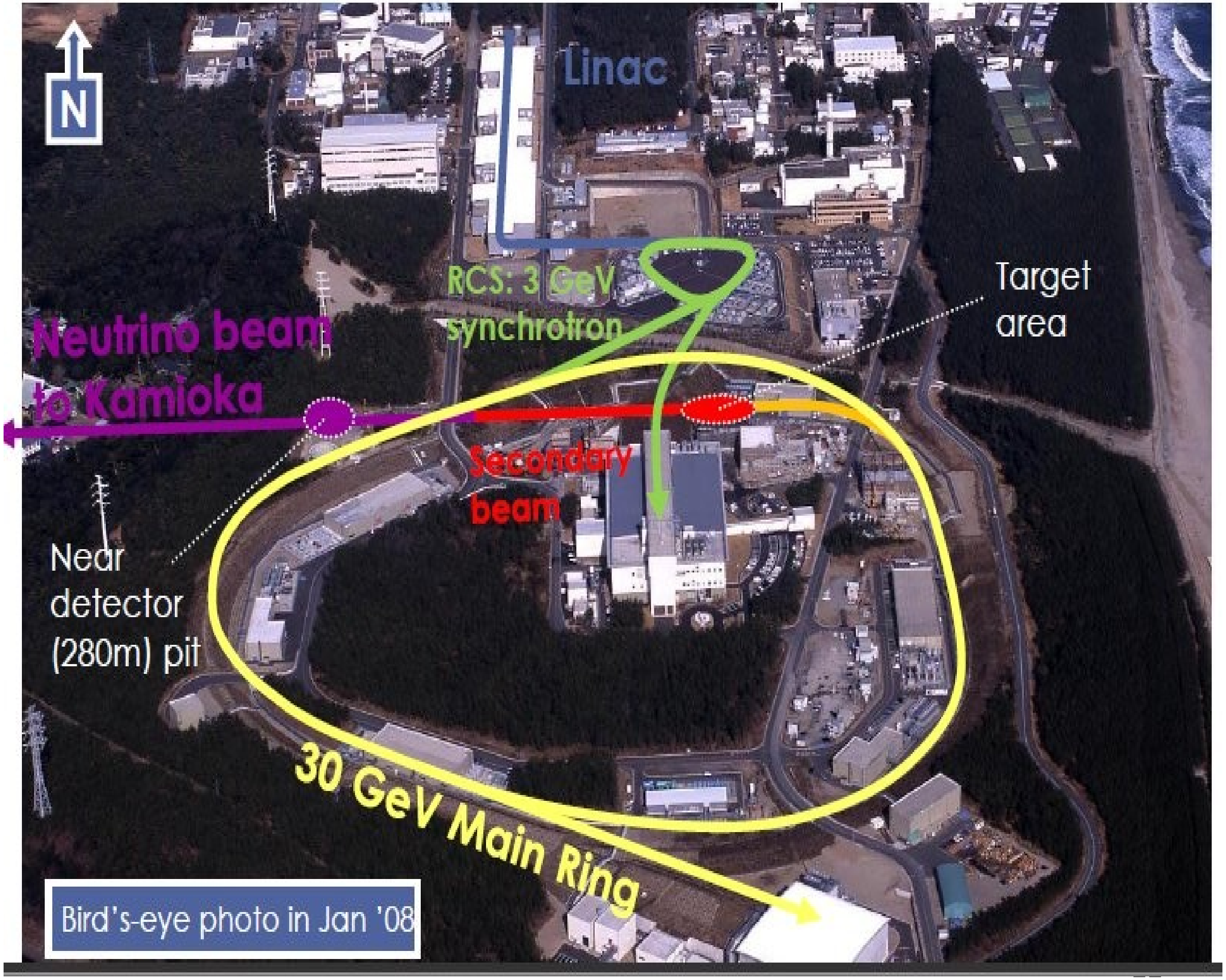
2013 ν_μ Disappearance



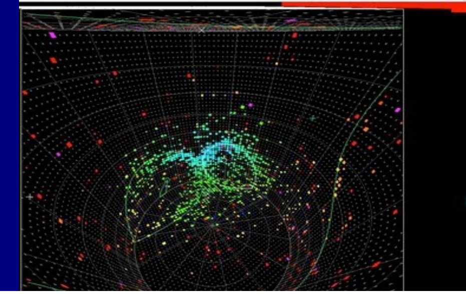
JPARC Beamline

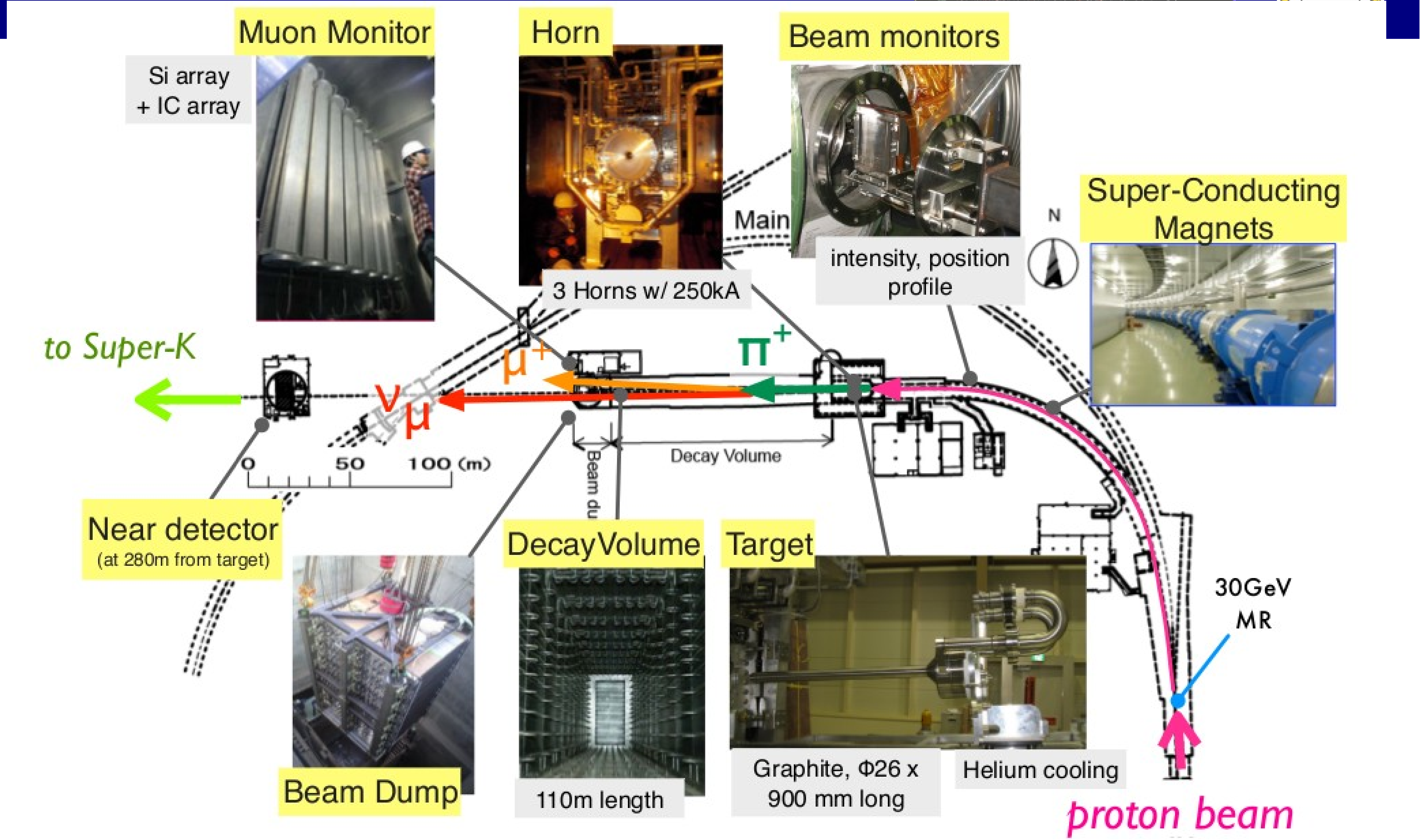


- Located in Tokai-village, 60km N.E. of KEK
- Completed in 2009
- MR
  - 1567.5 m circum.
  - Tp = 30GeV
  - 8 bunch (h#=9)
  - Rep cycle: 2.48sec (now)
- Design goal
  - RCS: 1MW
  - MR: 750kW
- MR achieved 220kW stable operation for neutrino experiment

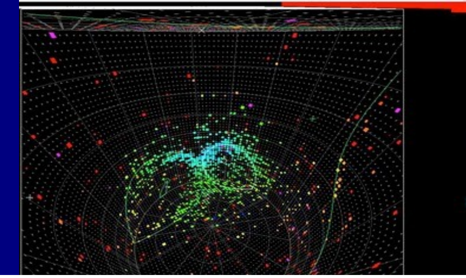


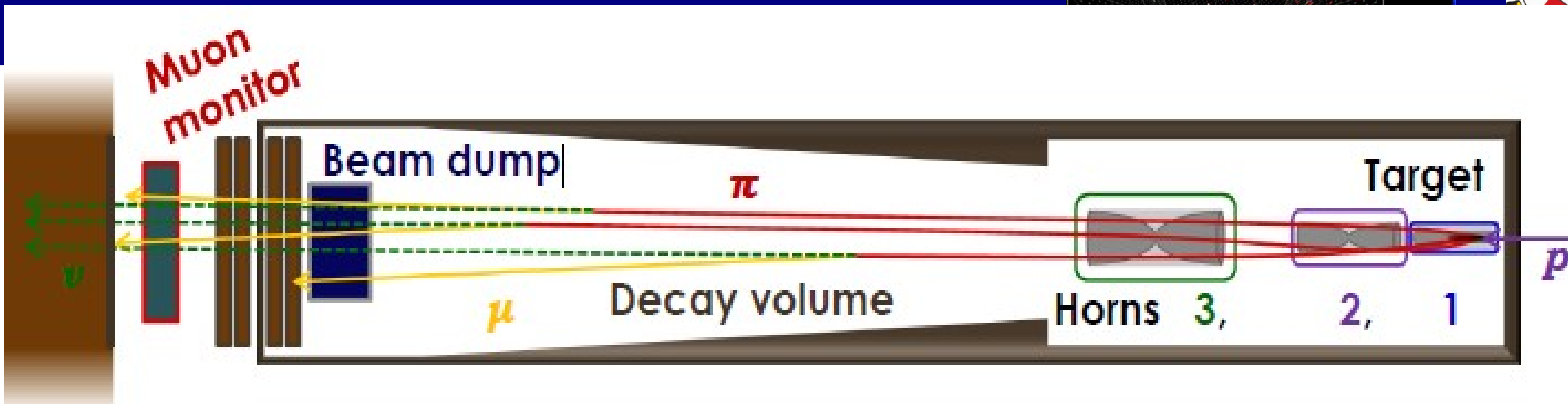
JPARC Beamline



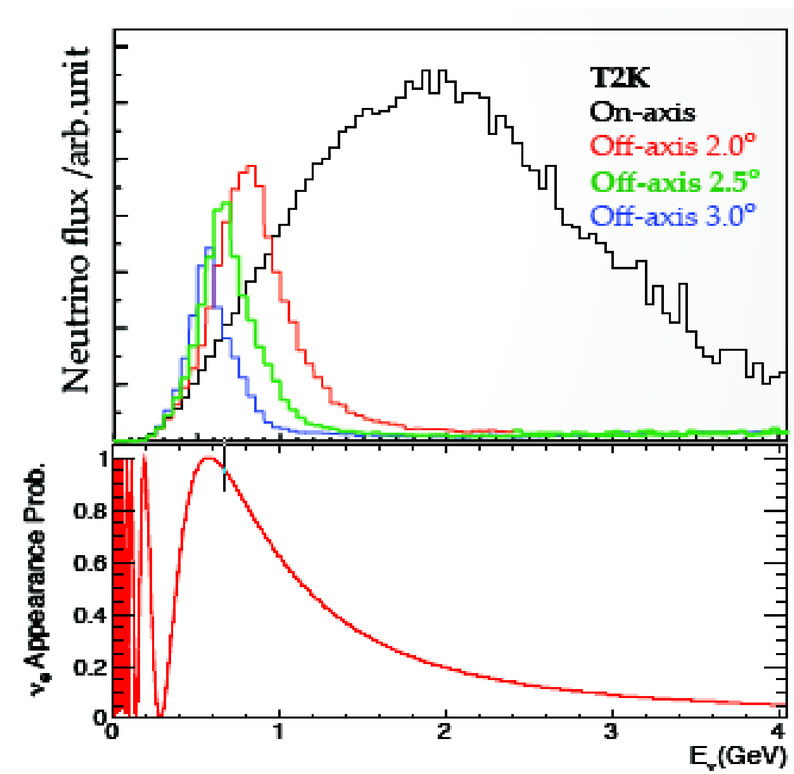


The Beam

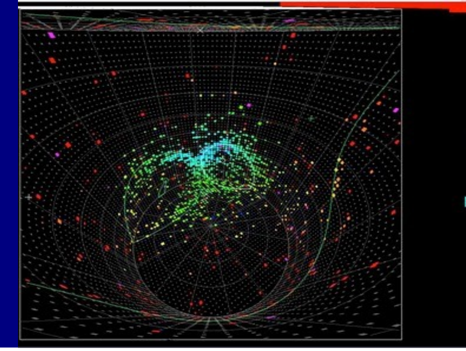




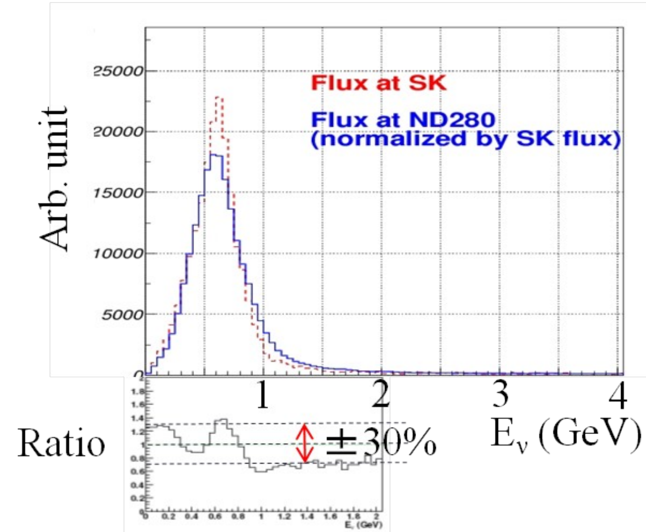
- ν_μ from pion decay
- Off-axis beam
  - concentrates flux around oscillation maximum
  - eliminates high-energy tail
  - Ideal for ν_e appearance
- Wrong sign background and beam ν_e present at a few %



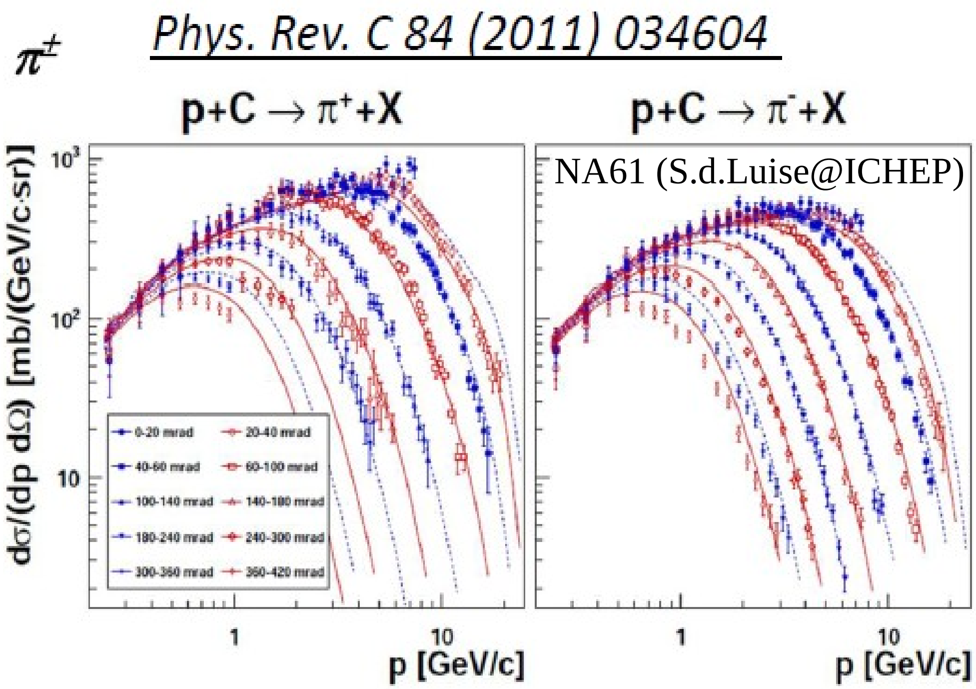
Beam Flux Tuning

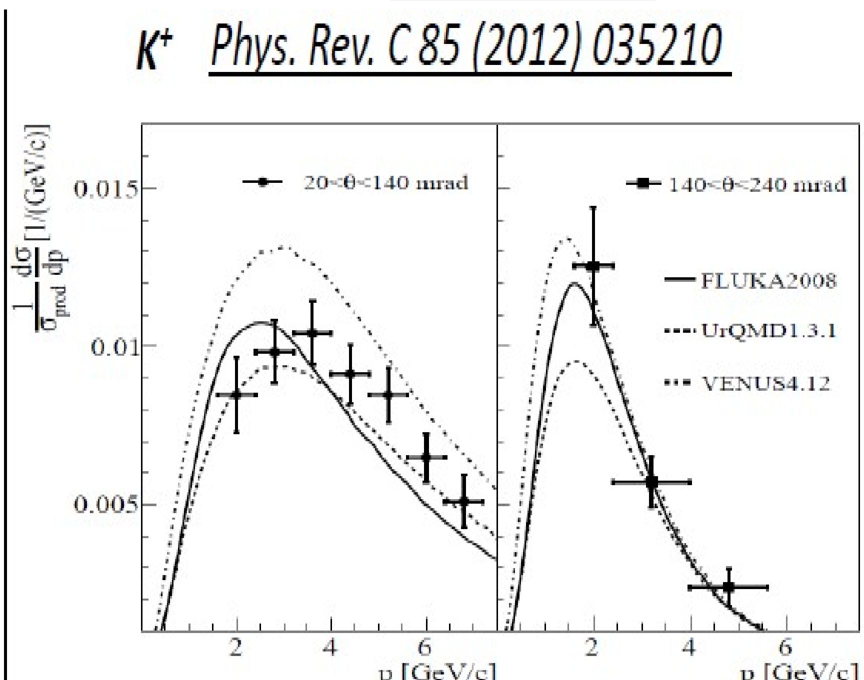


- Flux & Near to far flux extrapolation are governed by
  - parent hadron (p/K..) production (p&q dist.)
  - Beam line geometry (controllable)
- Hadron production measurements by NA61/SHINE CERN experiment with T2K replica target have been critical

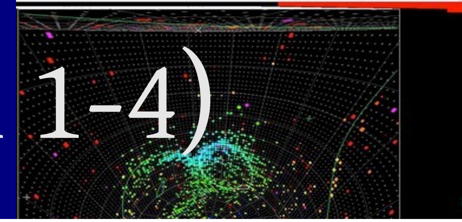


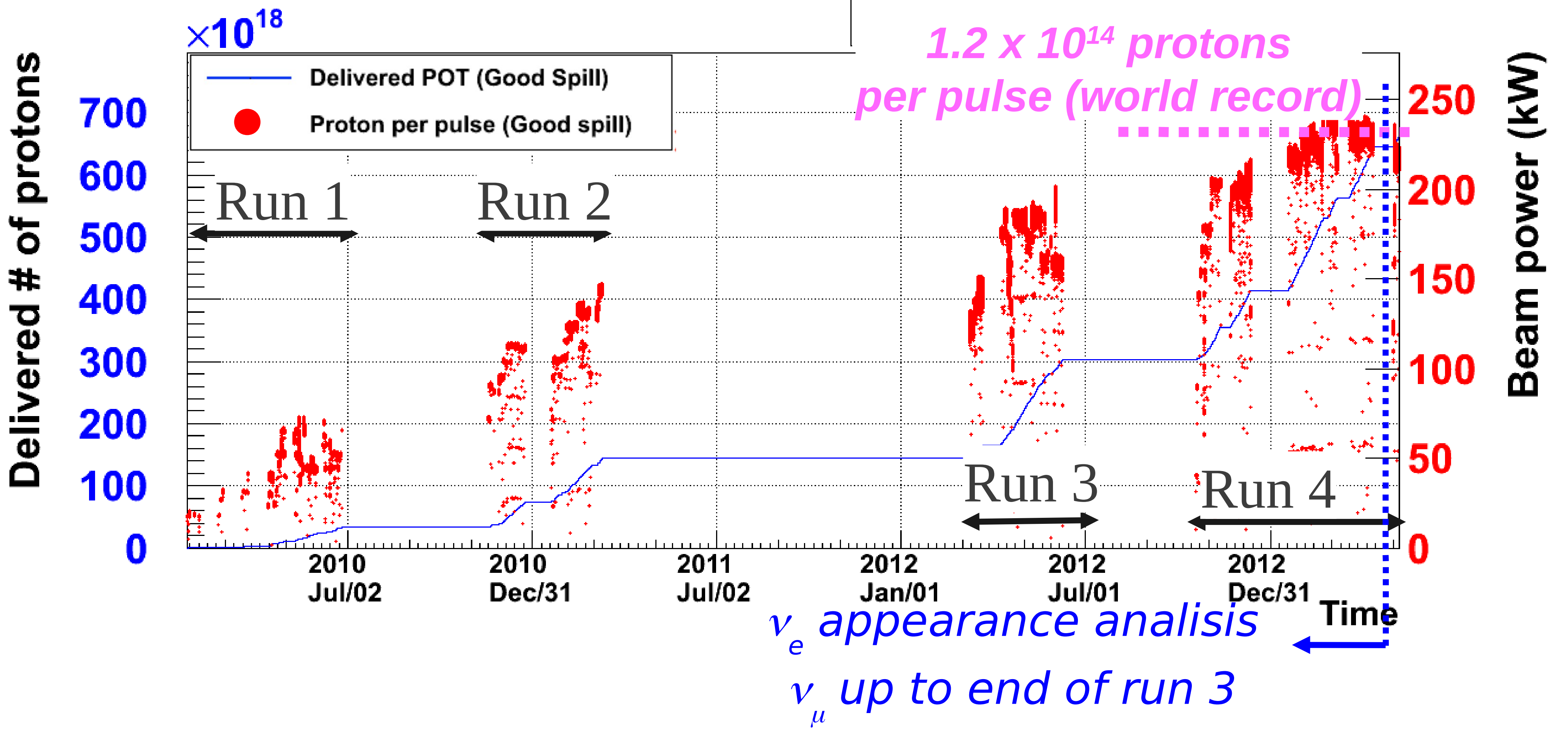
σ_{prod} (pC@31GeV/c)= 229.3 ± 1.9 ± 9.0 (mb)





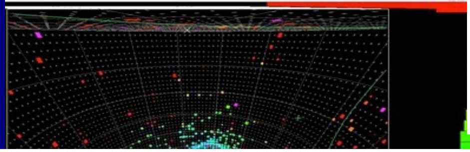
Data Taking (Run 1-4)



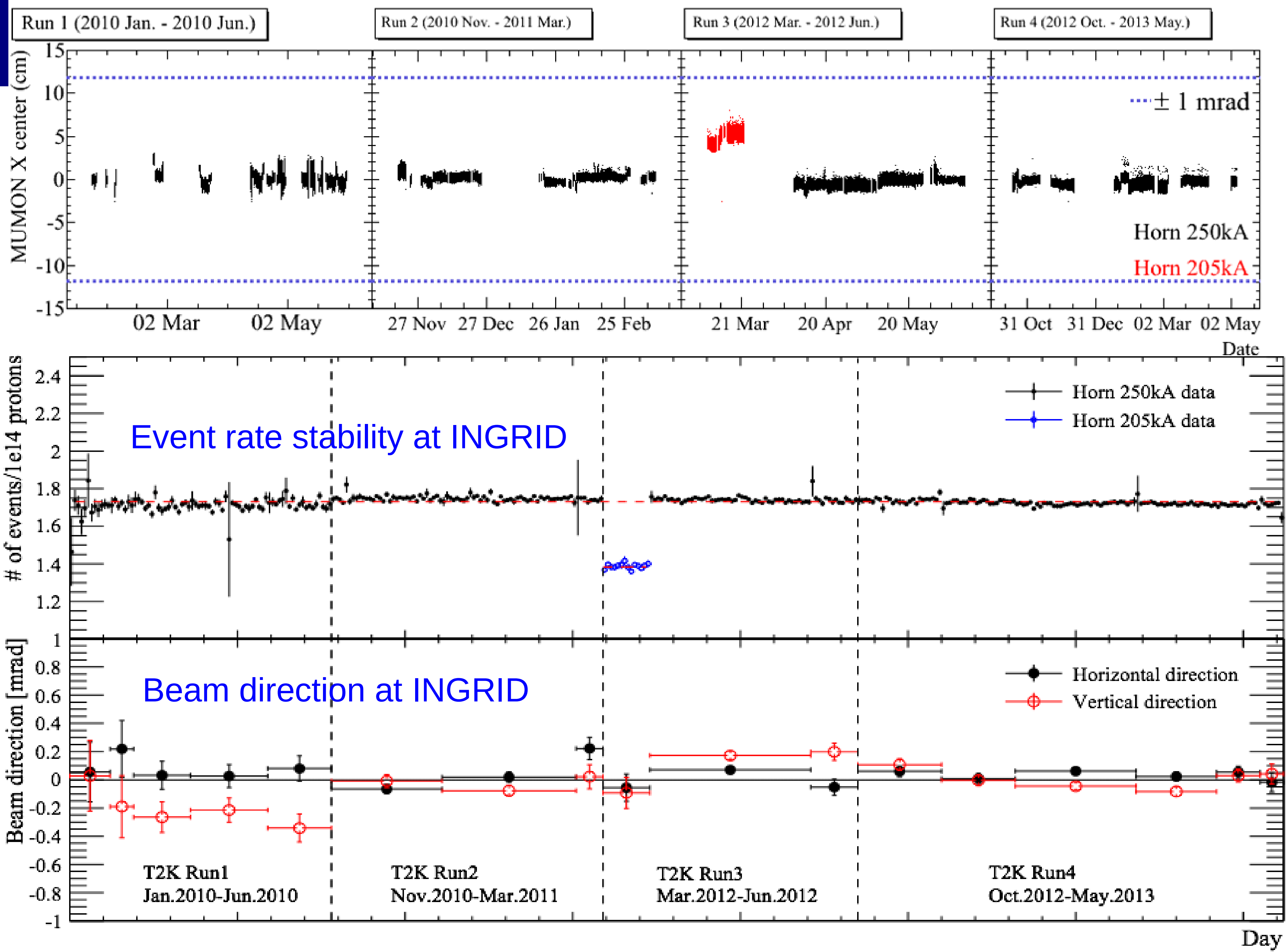


Results possible due to efforts of J-PARC accelerator division + related people.
Running at 220 kW for much of Run 4 (**world record protons per pulse**)
6.39×10^{20} POT analyzed through April 12th (6.63×10^{20} through May)
Previous ν_e appearance result used 3.01×10^{20} POT
→ **Factor of 2.1 increase in statistics** (relative to 2012 analysis)

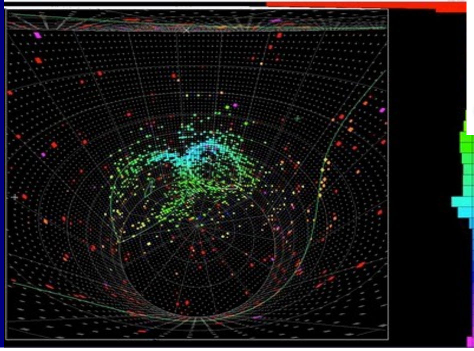
Beam Stability

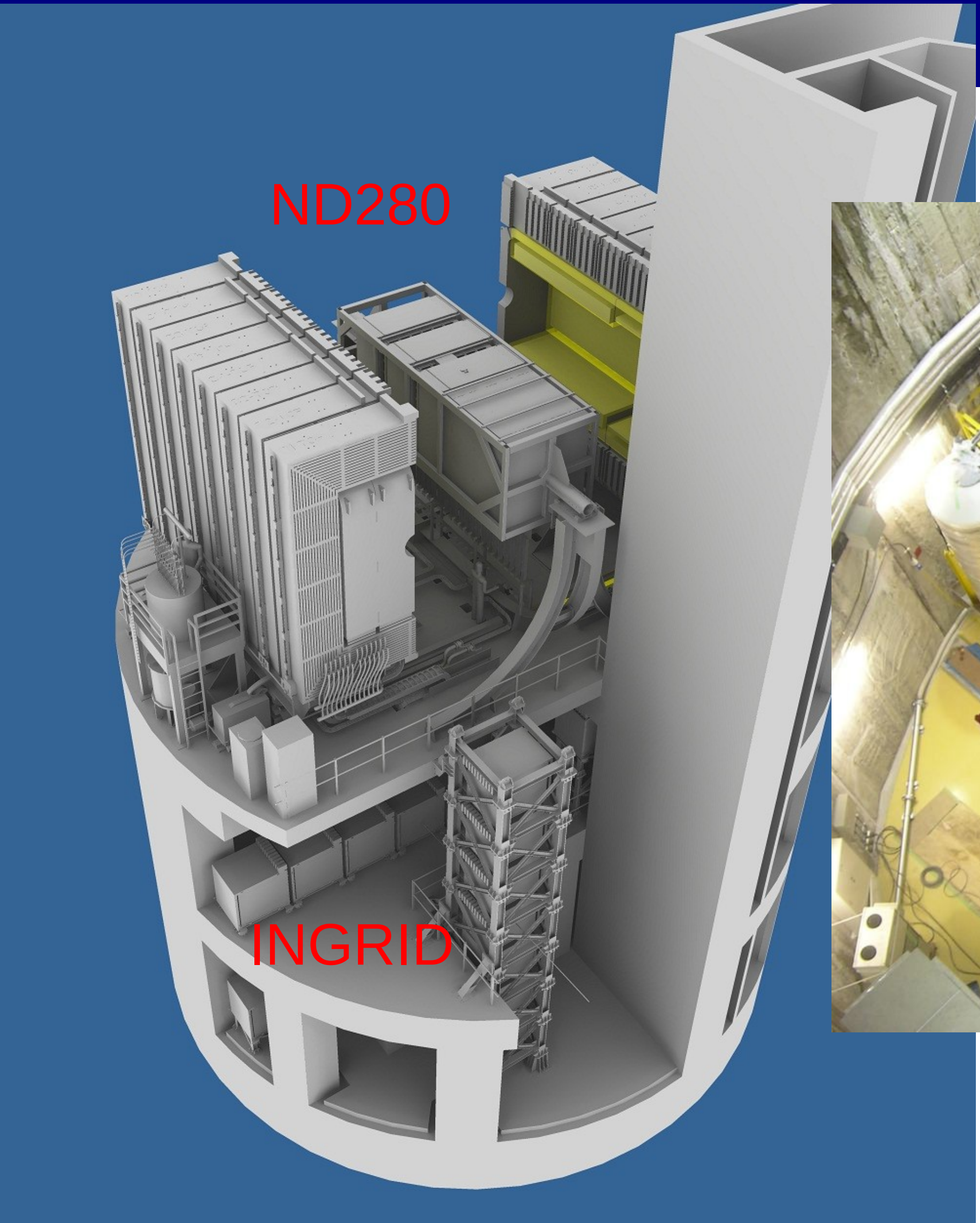


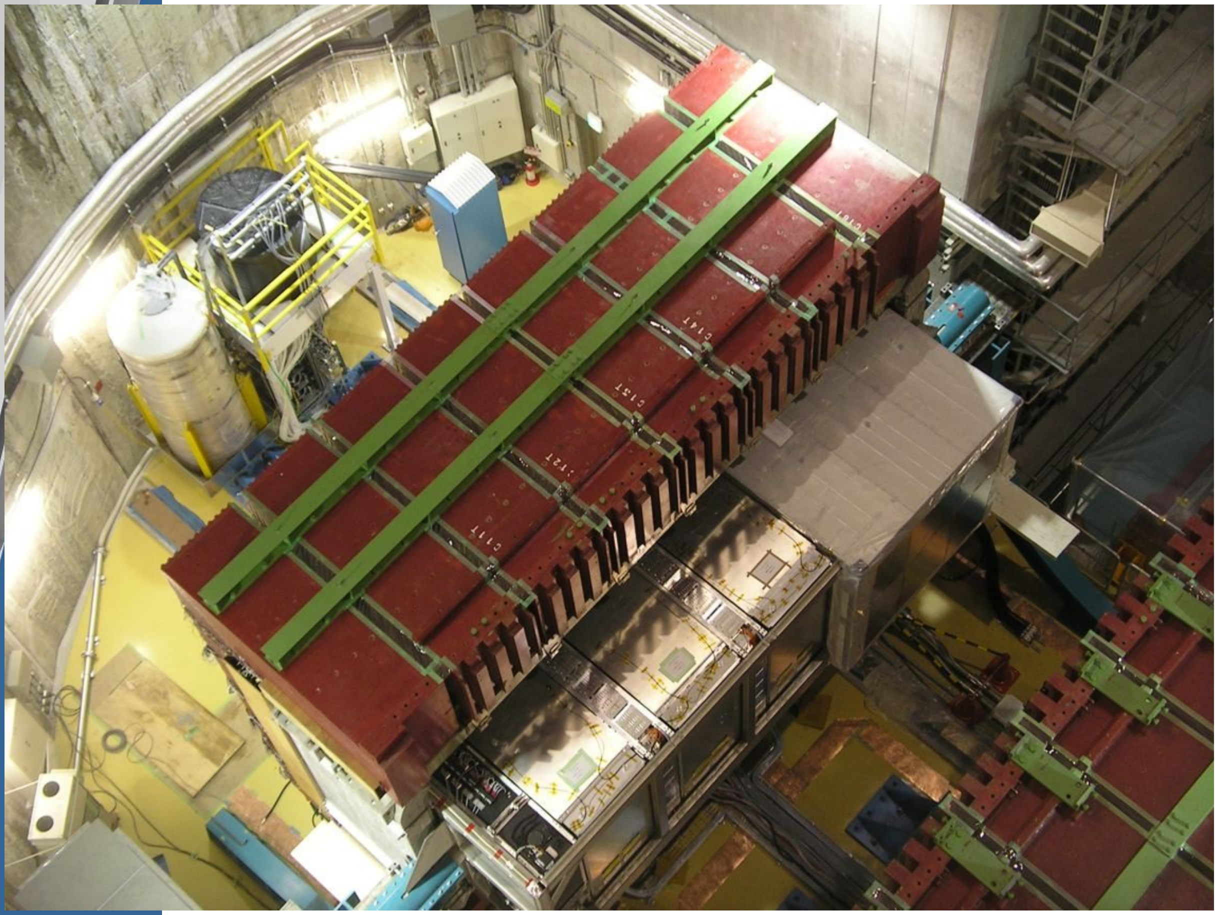
Profile center by muon monitor



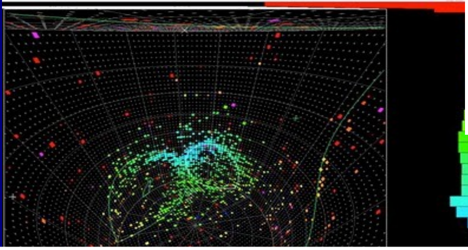
Near Detector Suite



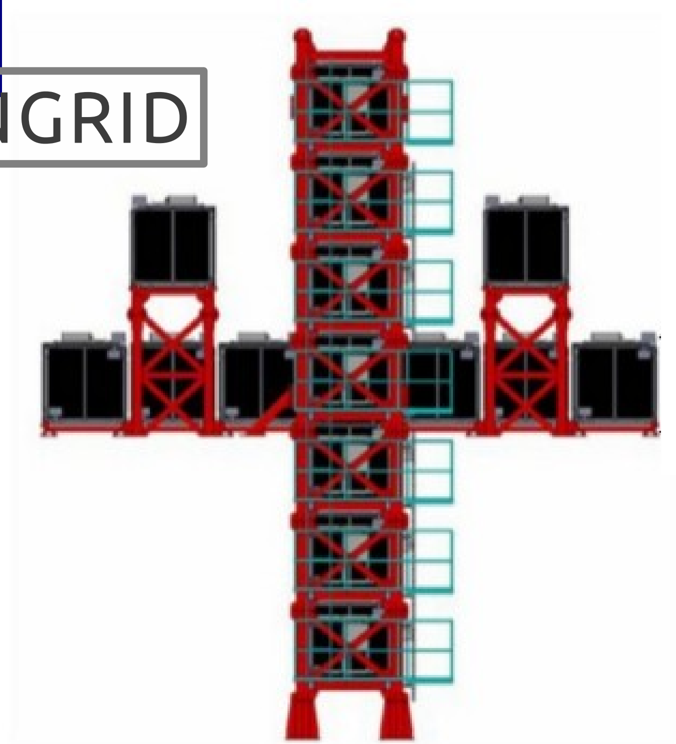




Near Detectors

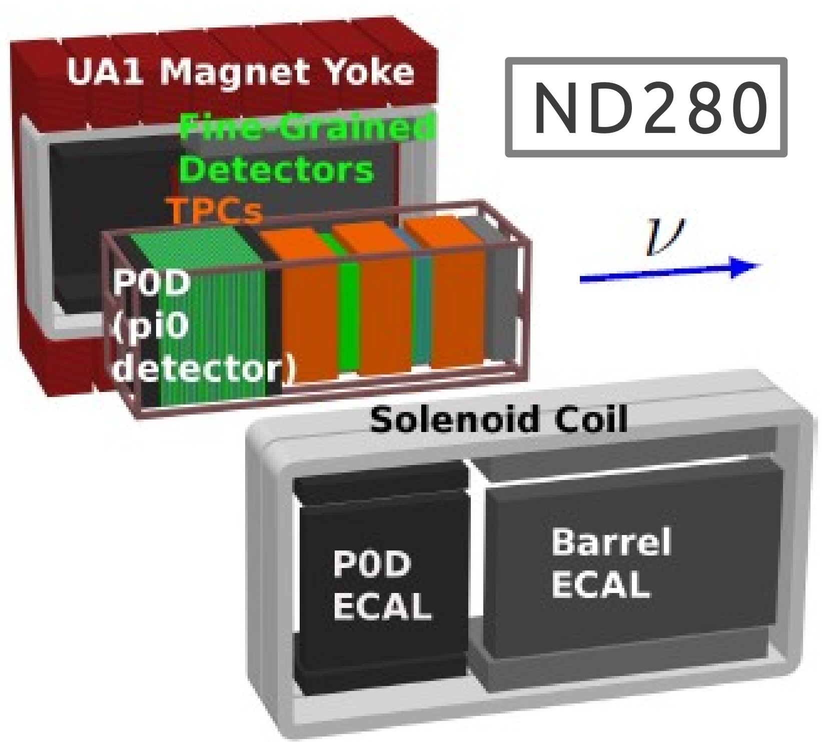


INGRID

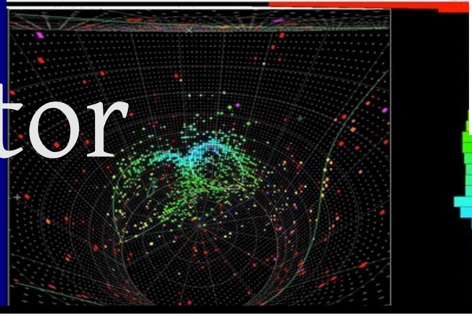


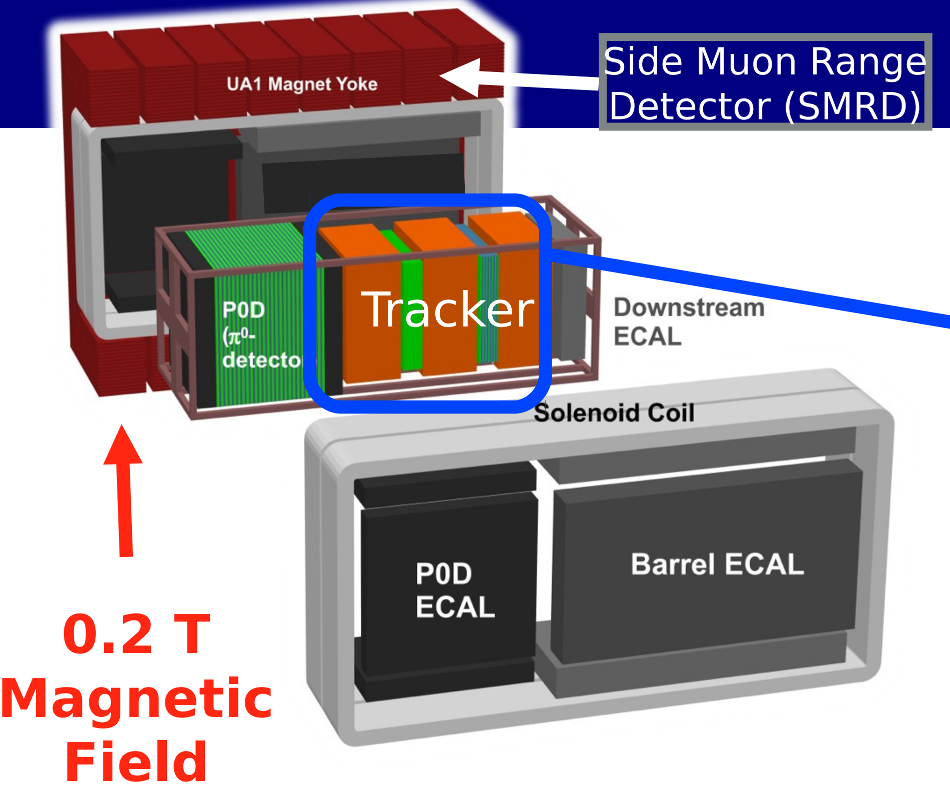
- On-axis detector 280 m from neutrino production point
- 16 iron-scintillator tracking calorimeters in cross profile
- 1 scintillator-only “proton module”
- Measures beam profile and CC inclusive rate

- Two fine grained detectors (C/$H_2$0 target) sandwiched by
- Three gas TPCs in
- UA1/NOMAD Magnet (0.2 T) with
- Upstream pi0 detector (P0D)

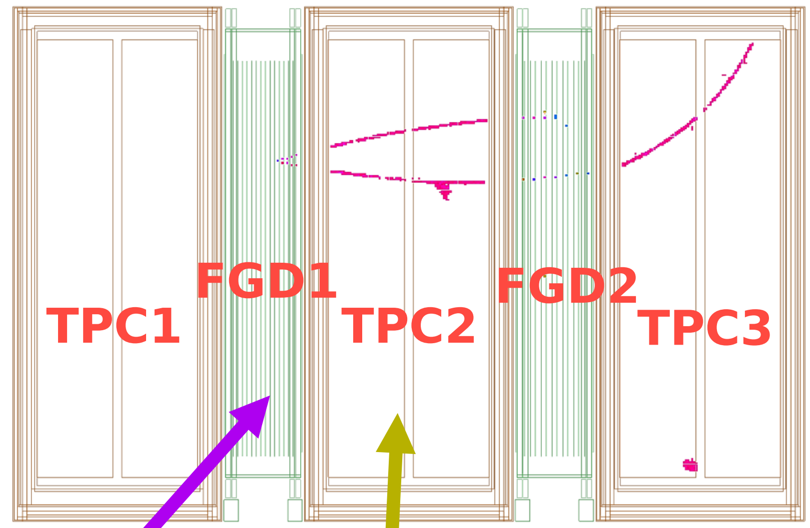


The Near Detector





CC Interaction in the Tracker



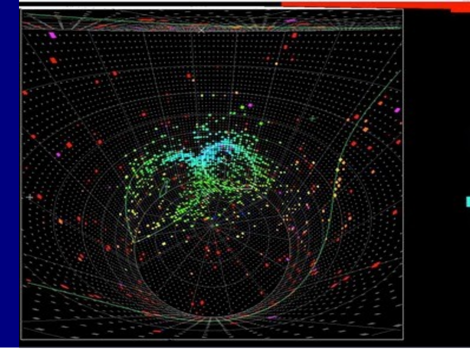
Fine-Grained Detectors (FGDs)

- Scintillator strips
- Provides neutrino target
- Detailed vertex information

Time Projection Chambers (TPCs)

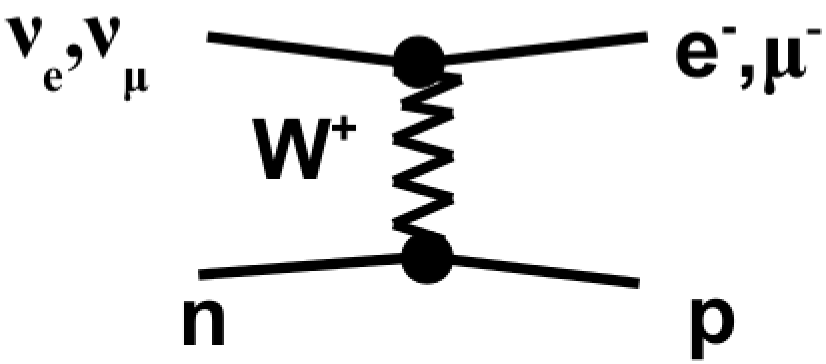
- Gas ionization chambers
- Track momentum from curvature
- Particle ID from dE/dx

Neutrino Interactions @ 0.1-2 GeV



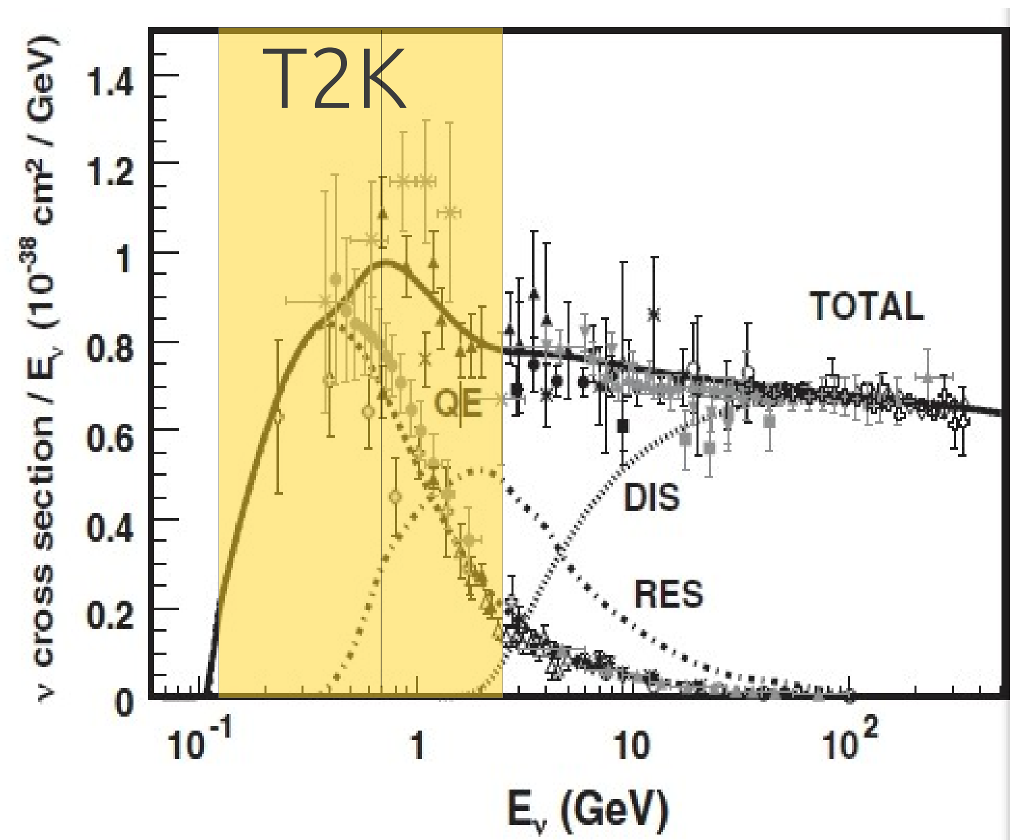
Formaggio & Zeller, Rev. Mod. Phys. 84 (2012)

Quasielastic dominated



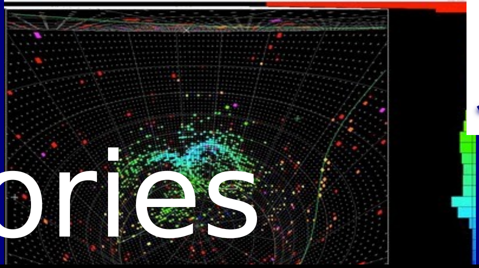
T2K signal at SK

CCQE

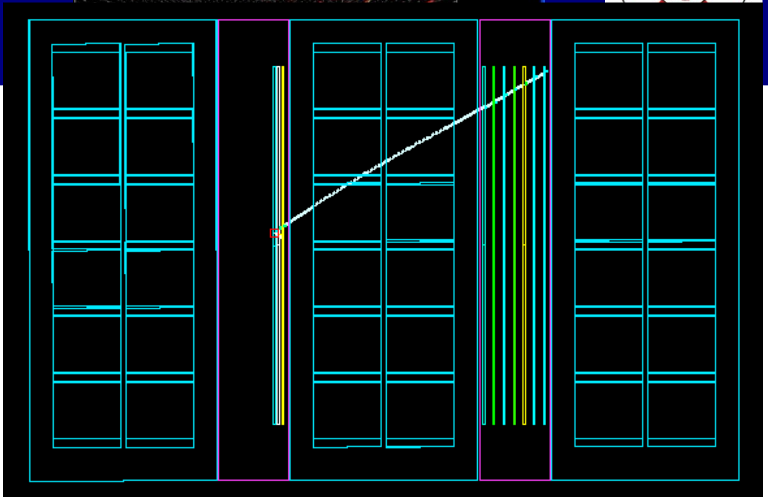


For QE interaction, with binding Energy Eb:

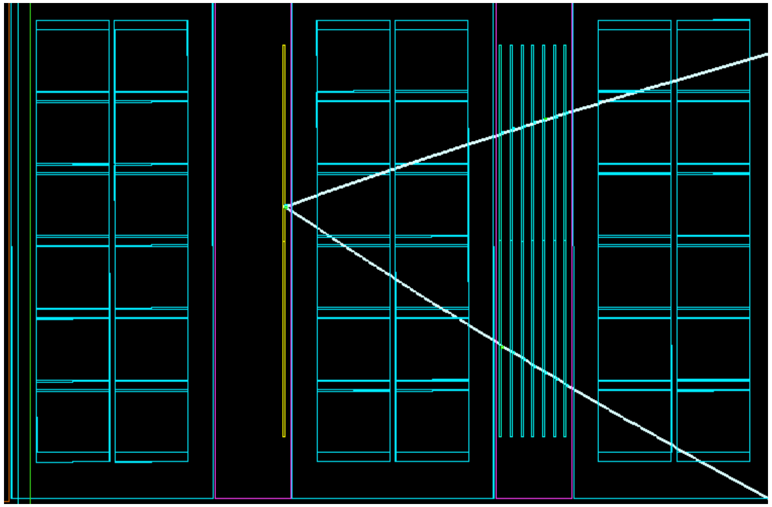
$$E_{\text{reco}} = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu \cos\theta_\mu)}$$



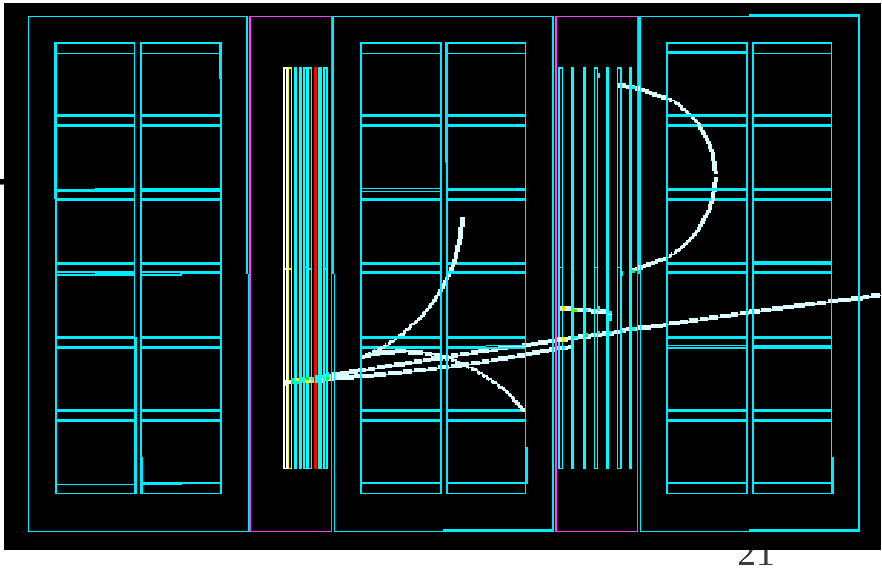
ND280 Event Categories



- Charged current (CC) with 0π

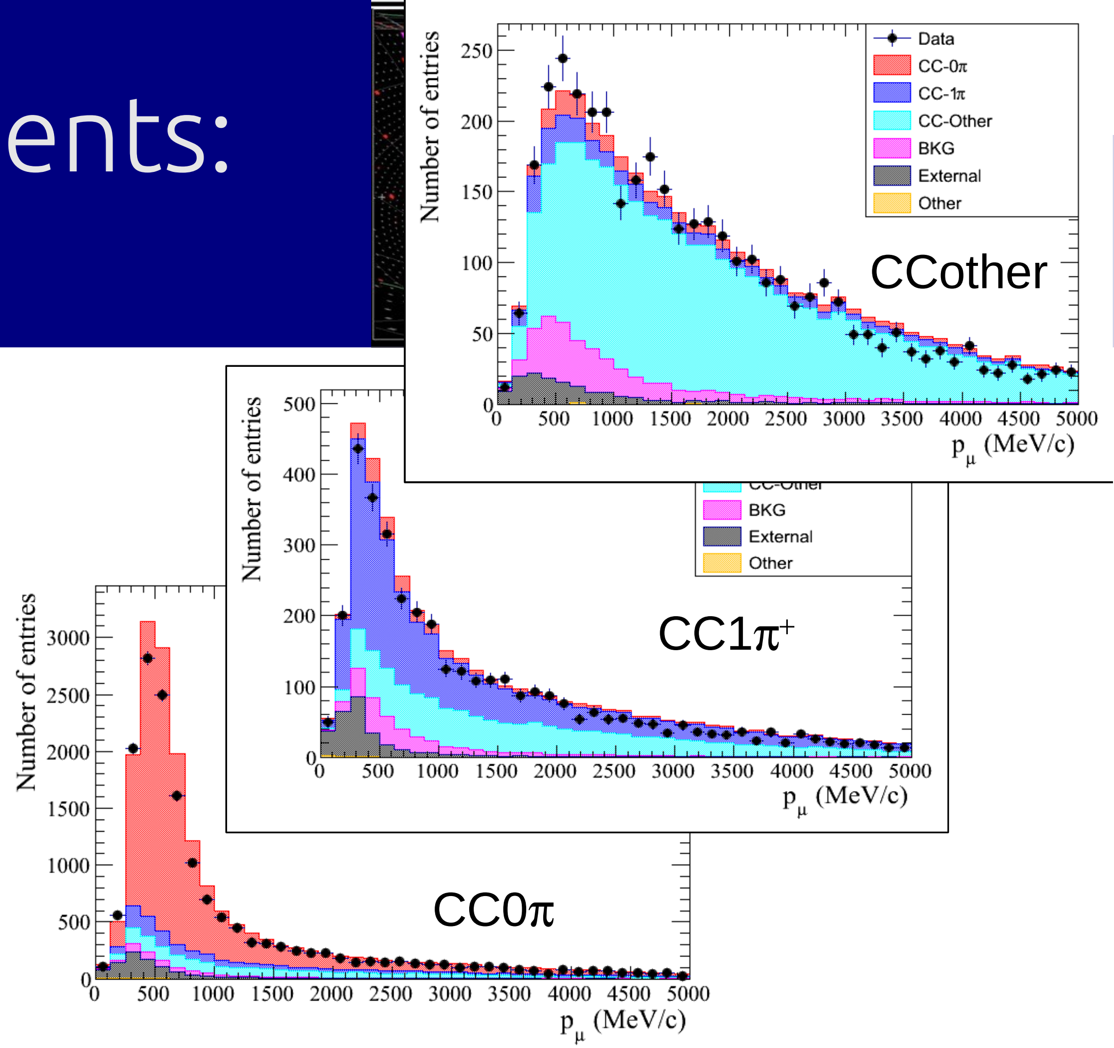


- CC 1π+



- CC Other (≥1π- or π0 ,or >1 π+)
  - π0 candidates have identified electrons in the TPC
- Disappearance analysis joins CC 1π+ and CC other together

Analysis Improvements: ND280

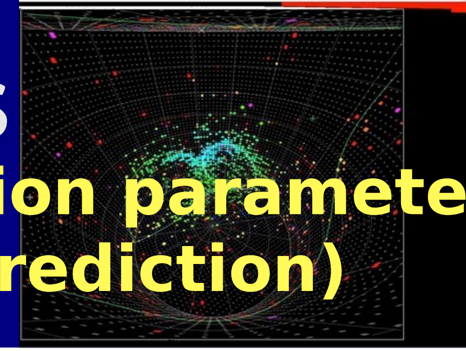


- Separate the CC sample into three subsamples:
  - CC0π: **no pions** in the final state
  - CC1π+: exactly **1 π+** in the final state
  - CCother: **>1 π+** OR **>0 π-** OR **>0 tagged photons**

- Higher purities for all 3 samples, relative to the 2012 analysis
- Much better samples for constraining CCQE and CCπ+ cross section parameters

	CC0π purities	CC1π purities	CCother purities
CC0π	72.6%	6.4%	5.8%
CC1π	8.6%	49.4%	7.8%
CCother	11.4%	31%	73.8%
Bkg(NC+$\bar{\nu}$)	2.3%	6.8%	8.7%
Out FGD1 FV	5.1%	6.5%	3.9%

Near Detector Constraints



Goal: Constrain ν-flux and cross section parameters (used for T2K far detector MC prediction)

ν-Flux

ν_μ and ν_e fluxes are correlated

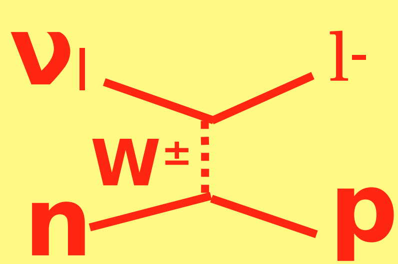
$$\pi^+ \to \mu^+ \nu_\mu$$
$$\hookrightarrow e^+ \nu_e \bar{\nu}_\mu$$

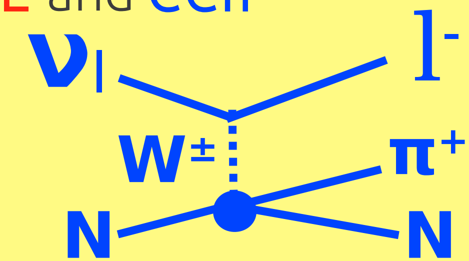
Can use ν_μ measurement to constrain the ν_e flux

External constraints from CERN experiment NA61

Cross Sections

Main CC interactions relevant to T2K are CCQE and CCπ^+





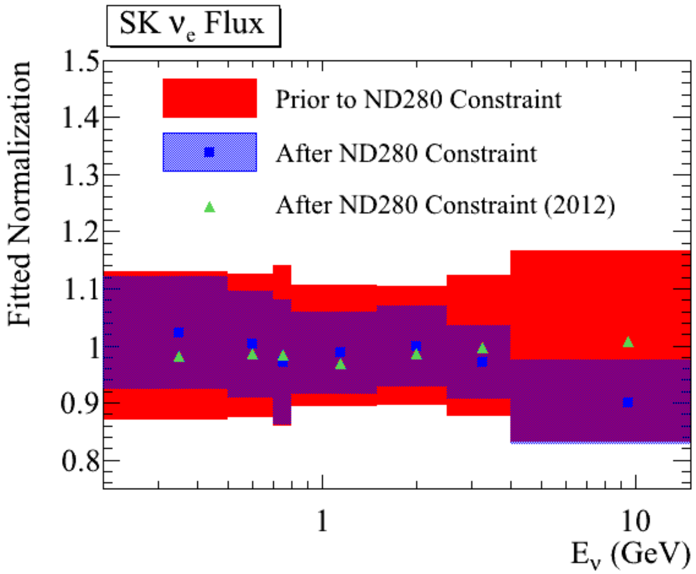
Need to constrain the parameters of these interactions: M_A^{QE}, M_A^{RES}, etc.

External constraints from MiniBooNE

The ν_μ spectrum at the near detector is fit to extract flux and cross section constraints at the far detector

2013 Near Detector Constraint

- Significant reduction in the far detector event rate errors
- Uncertainties on the cross section parameters have been reduced
- Uncertainties on the flux parameters are also reduced



Error on Far Detector ν_e Prediction (After Near Detector Constraint)

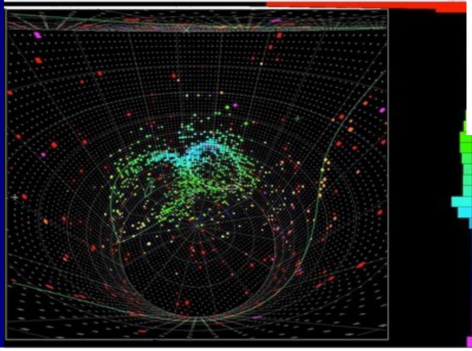
	Runs 1-3 (2012)	Runs 1-3 (2013)	Runs 1-4 (2013)
$\sin^2 2\theta_{13}=0.1$	4.7%	3.5%	3.0%
$\sin^2 2\theta_{13}=0.0$	6.1%	5.2%	4.9%

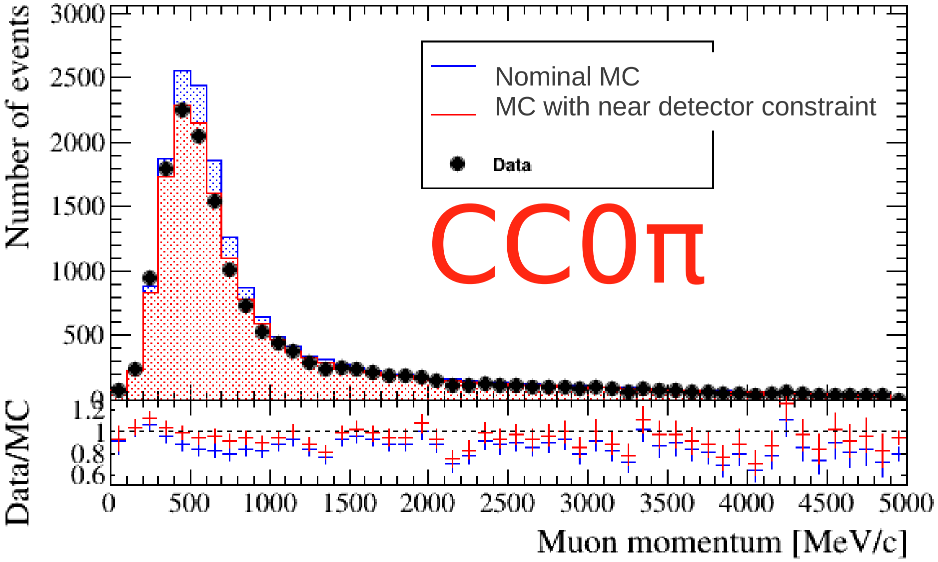
Error on Cross Section Parameters (After Near Detector Constraint)

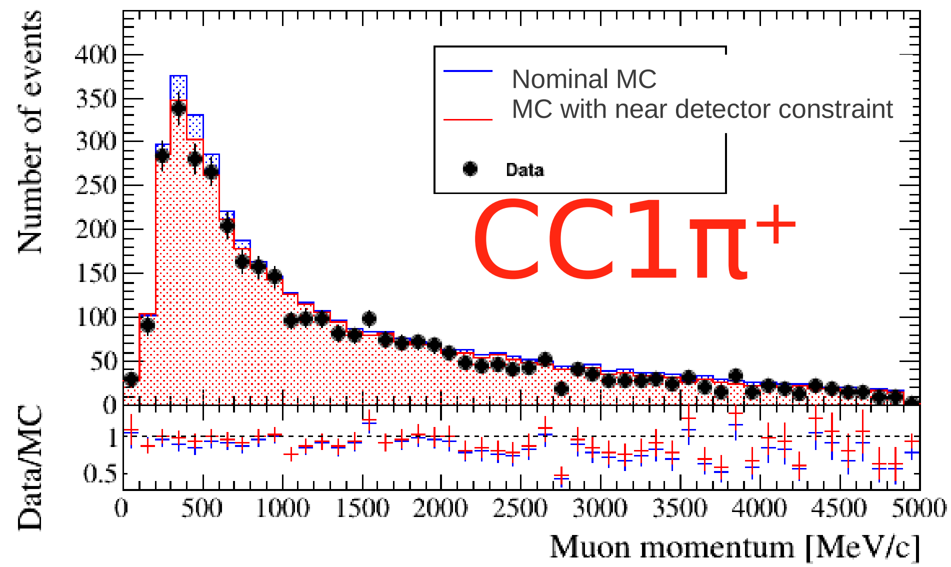
Parameter	Runs 1-3 (2012)	Runs 1-4 (2013)
M_A^{QE} (GeV/c²)	1.27 ± 0.19	1.22 ± 0.07
M_A^{RES} (GeV/c²)	1.22 ± 0.13	0.96 ± 0.06
CCQE Norm.	0.95 ± 0.09	0.96 ± 0.08
CC1π Norm.	1.37 ± 0.20	1.22 ± 0.16

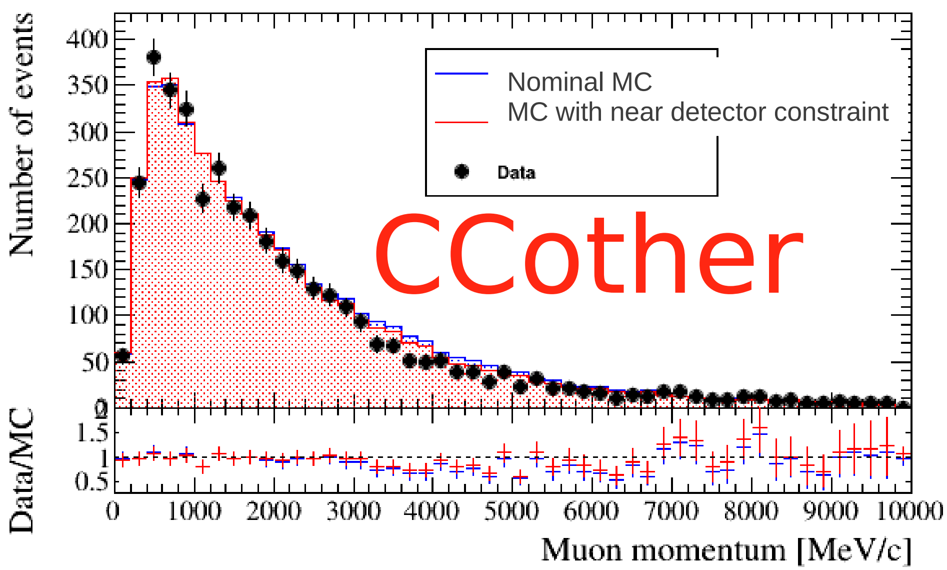
Near Detector Data

simulation includes constraint from near detector



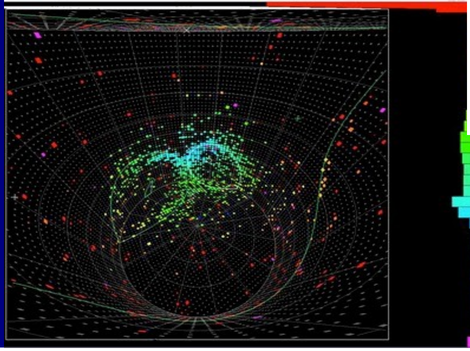






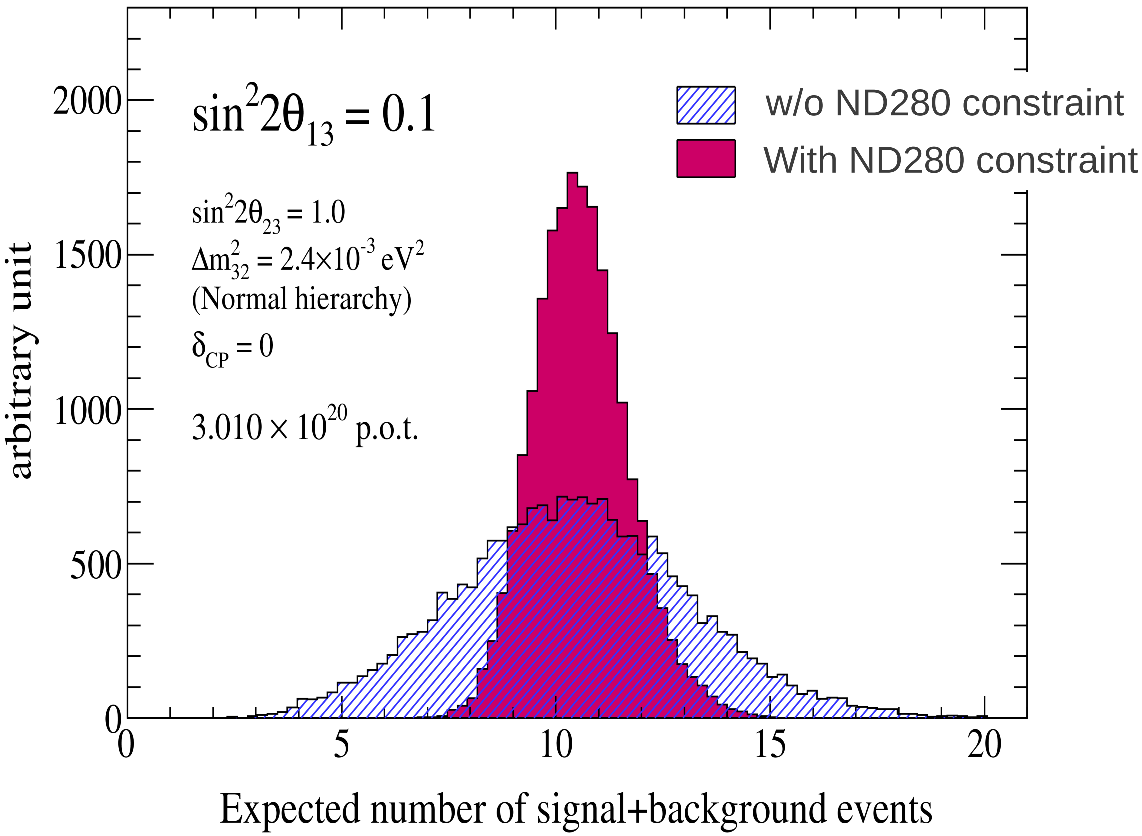
data/MC agreement is improved by the near detector constraint

ND280 Constraint

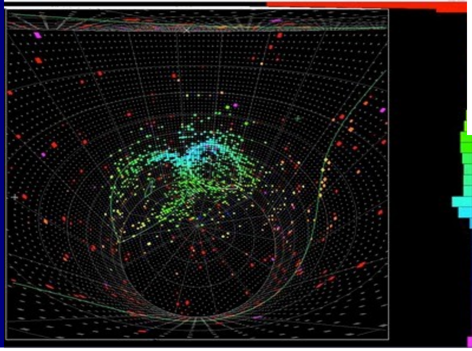


- Fit model to measured (p_μ,θ_μ) distributions for CC0π, CC1π+ and CCother
- Flux and model uncertainties varied within their errors set by external data
- Correlation matrix from near detector constrained fit used for fitting far detector data.

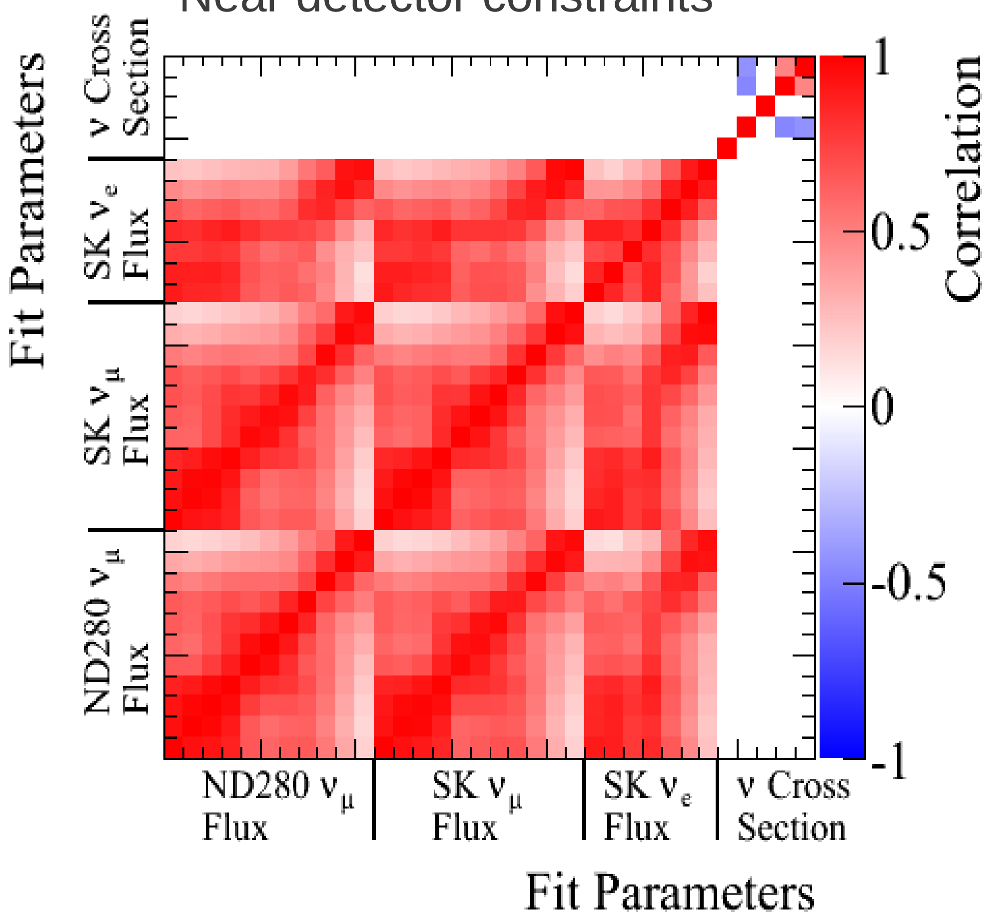
(example from 2012 ν_e analysis)



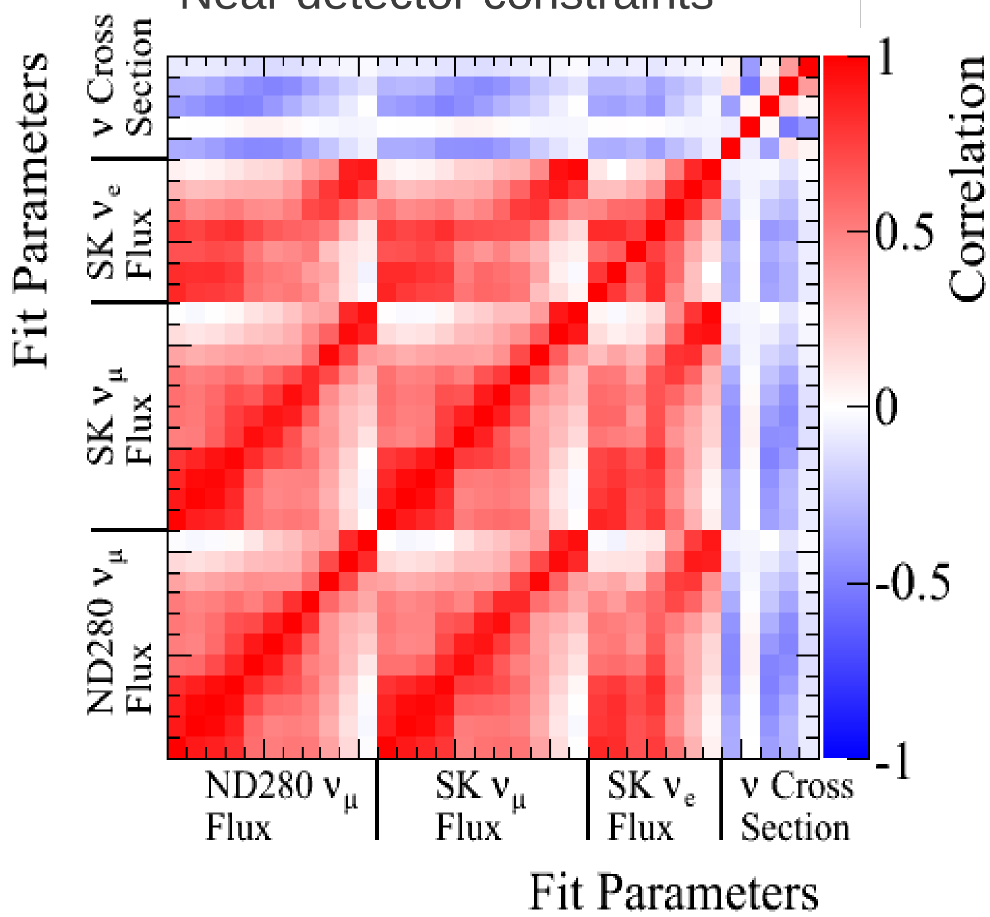
Parameter Correlations



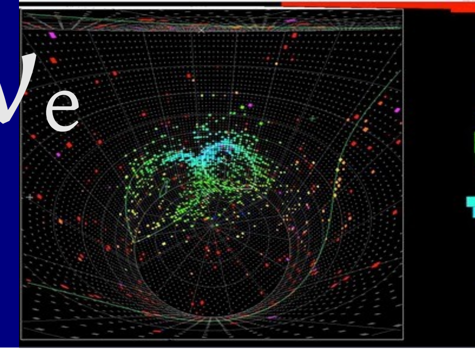
Correlations before including Near detector constraints



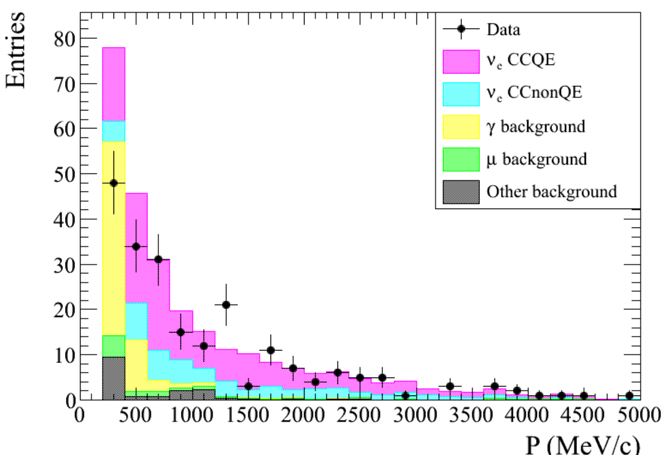
Correlations after including Near detector constraints



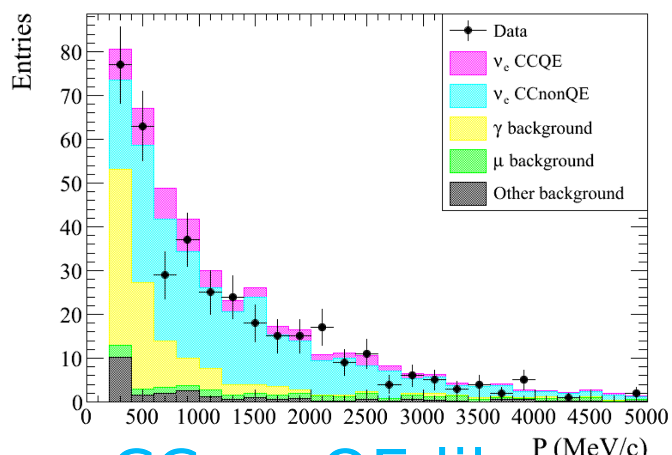
Near Detector Beam ν_e Measurement



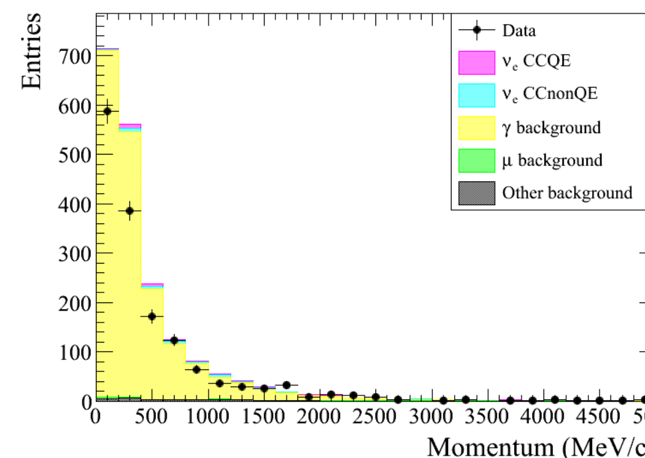
- For ν_e appearance, largest background is intrinsic ν_e contamination in the beam
- The intrinsic ν_e rate can be measured in the near detector



CCQE-like



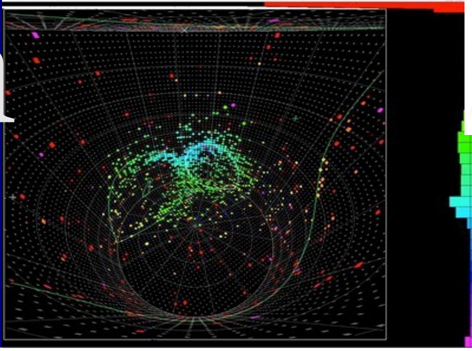
CCnonQE-like



γ Background Sample

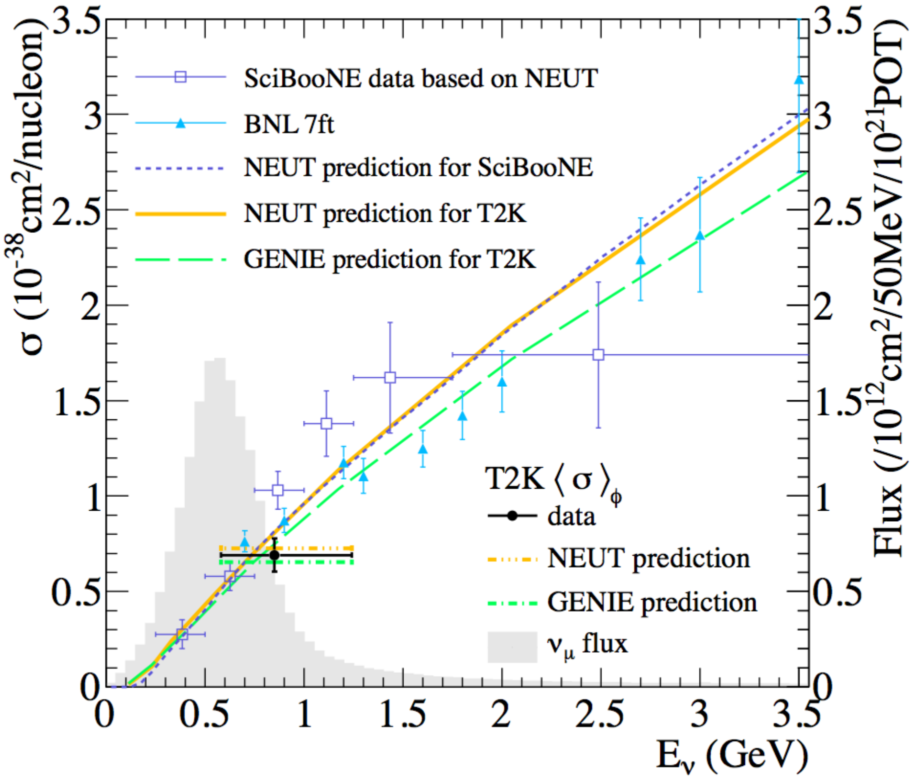
- Short-baseline ν_e's can also be used to search for sterile neutrinos

T2K Cross Section Measurements

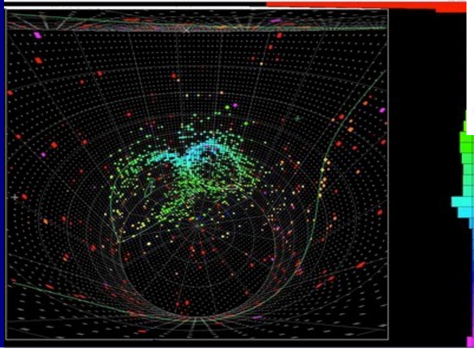


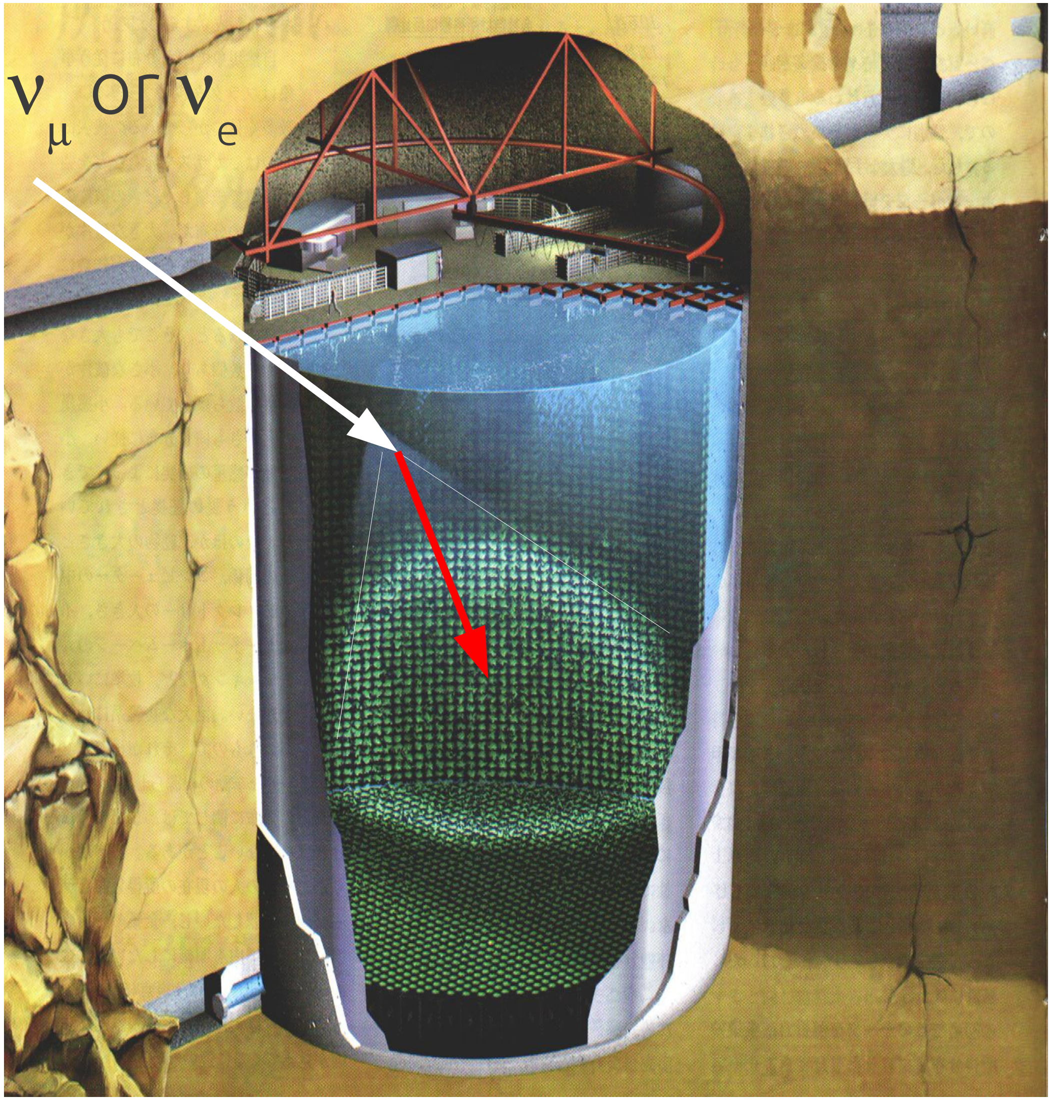
- The near detector oscillation analysis can be repurposed for cross section measurements
  - Event selection and detector systematic uncertainties are the same
- The T2K CC-Inclusive cross section measurement has now been published
  - Uses the same near detector event selection as the 2012 oscillation analysis
  - Phys. Rev. D 87, 092003 (2013)
- The CCQE sample from the 2012 oscillation analysis has been used to measure $\sigma_{CCQE}(E_\nu)$
- Additional cross section results are expected later this year

T2K CC-Inclusive Cross Section Measurement



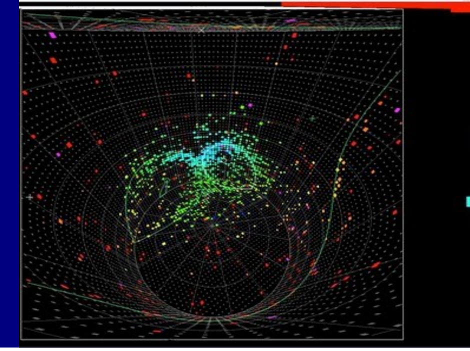
Far Detector
Super-Kamiokande



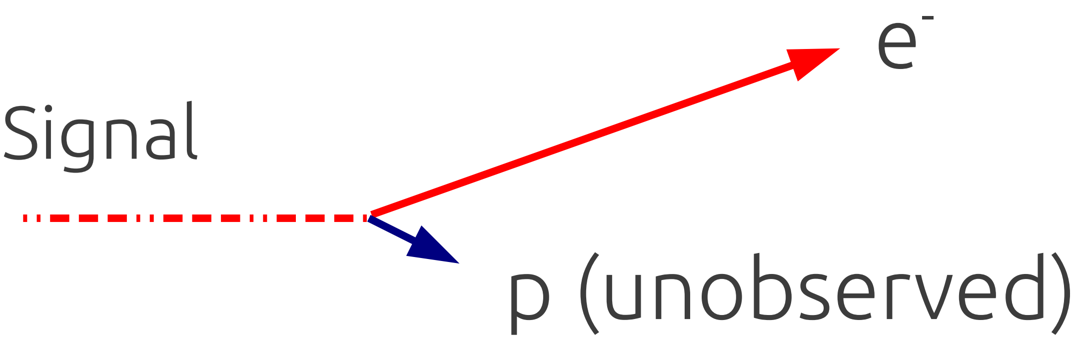


- 22.5 kton fiducial water Cerenkov detector
- Look for electron for CC neutrino interactions
- Cerenkov ring pattern can be used to distinguish lepton flavour
- Well-understood and stable detector

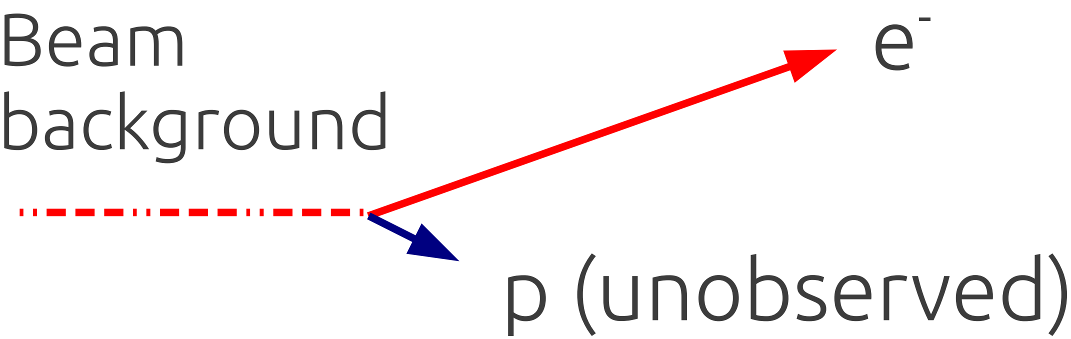
T2K far detector
ν_e Signal & Background



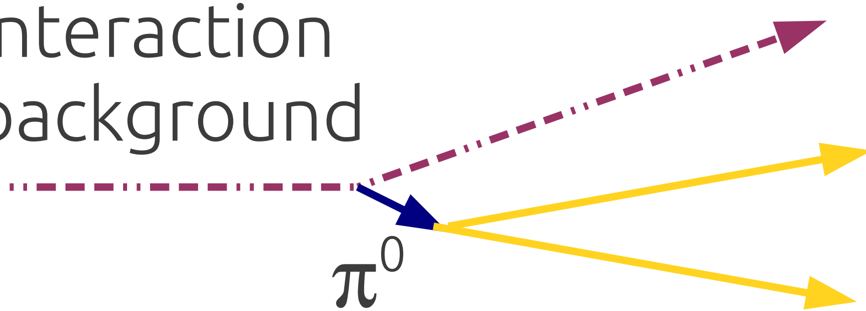
Signal

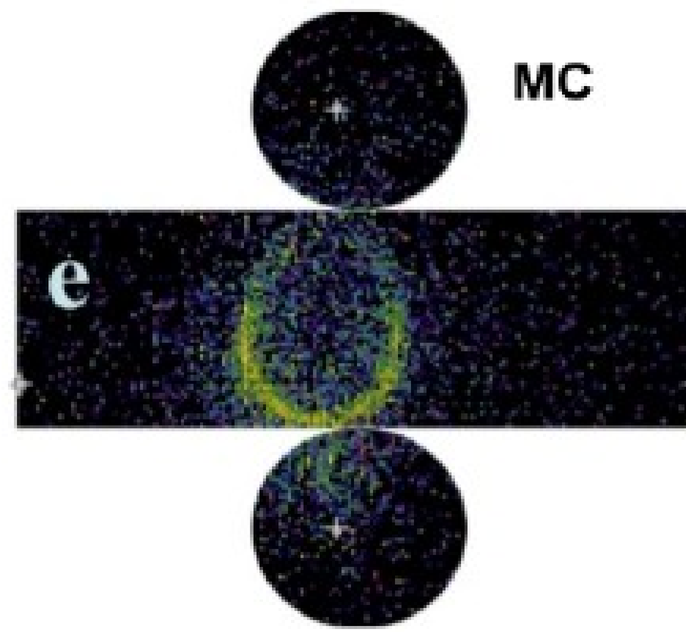


Beam background



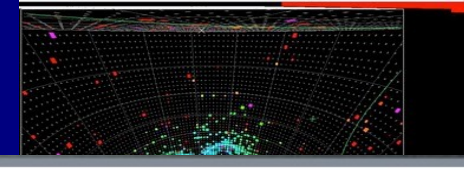
Interaction background

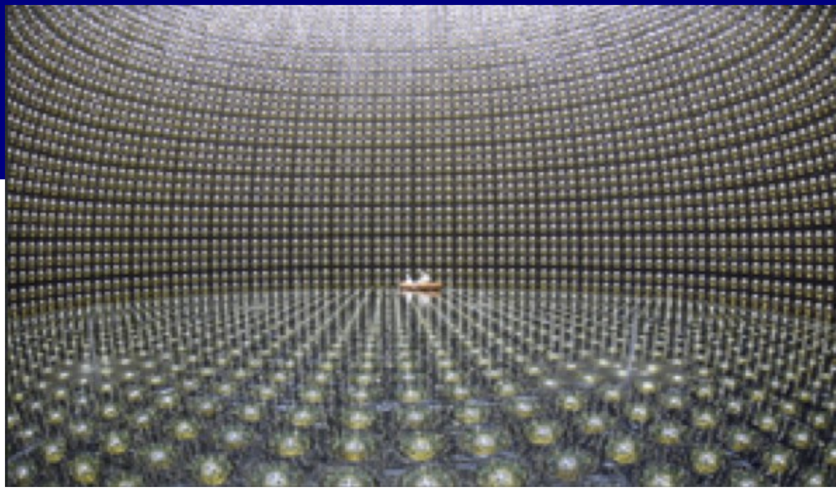


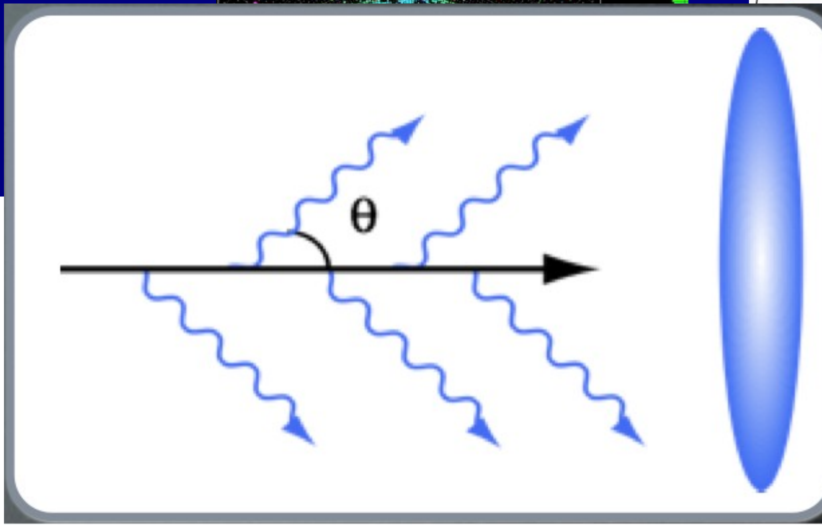


Identify 2 e-like rings
Asymmetric decays or overlapping photons are reducible bg.

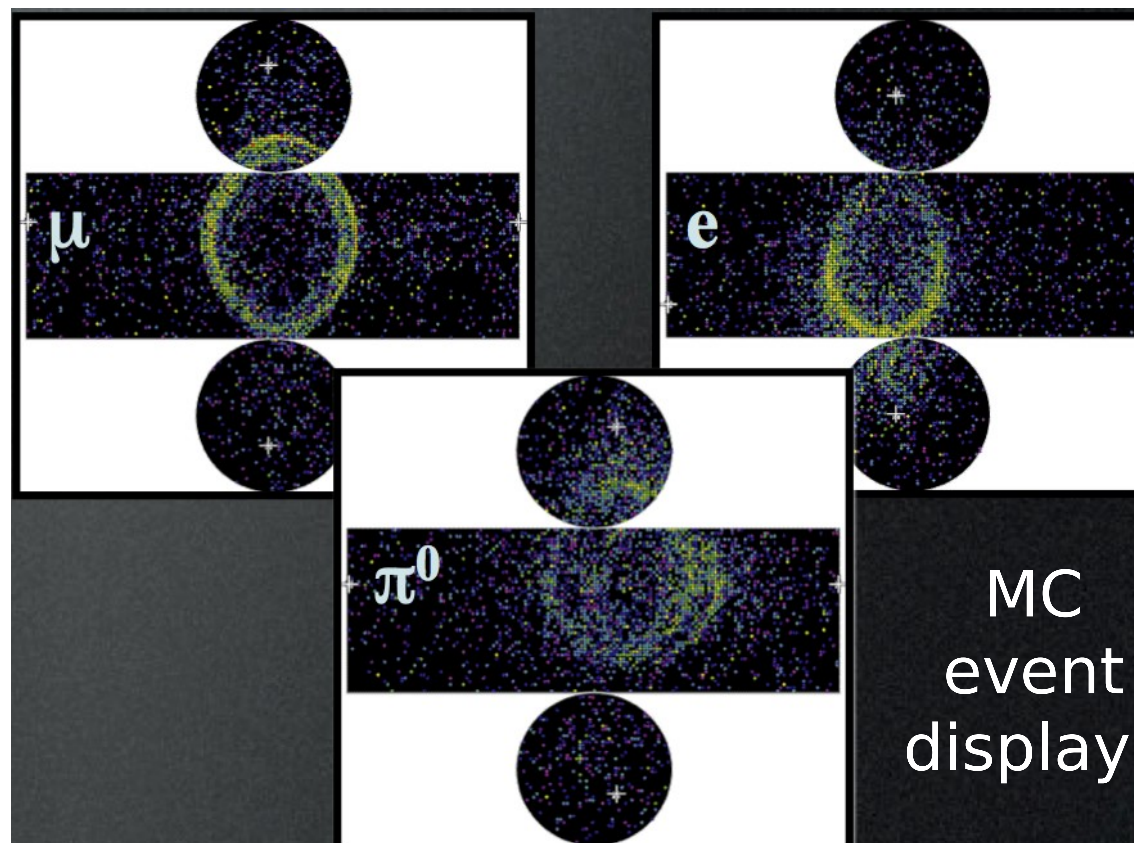
The T2K Far Detector



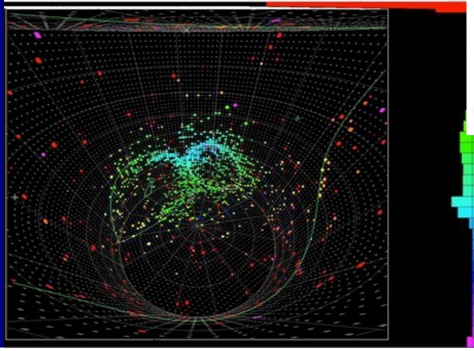




- 50 kton water Cherenkov detector
- **μ detection**
  - Less scattering ⇒ sharp rings
- **e detection**
  - More scattering ⇒ fuzzy rings
- **π^0 detection**
  - 2 electron rings ($\pi^0 \rightarrow 2\gamma$)
  - To separate from electrons, **MUST detect 2nd ring**



Analysis Strategy



Maximise a global likelihood with respect to oscillation, beam and cross section parameters

$$\mathcal{L}_{\mathrm{tot}}(\vec{b},\vec{x},\vec{o}) = \mathcal{L}_{\mathrm{pbeam}}(\vec{b}) \times \mathcal{L}_{\mathrm{NA61}}(\vec{b}) \times \mathcal{L}_{\mathrm{ext}-\nu}(\vec{x}) \times \mathcal{L}_{\mathrm{ND280}}(\vec{b},\vec{x}) \times \mathcal{L}_{\mathrm{SK}}(\vec{b},\vec{x},\vec{o})$$

T2K Beam Constraint

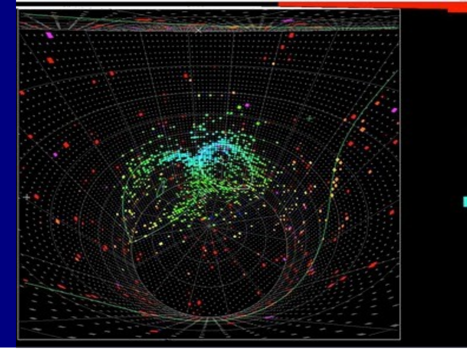
Super-K

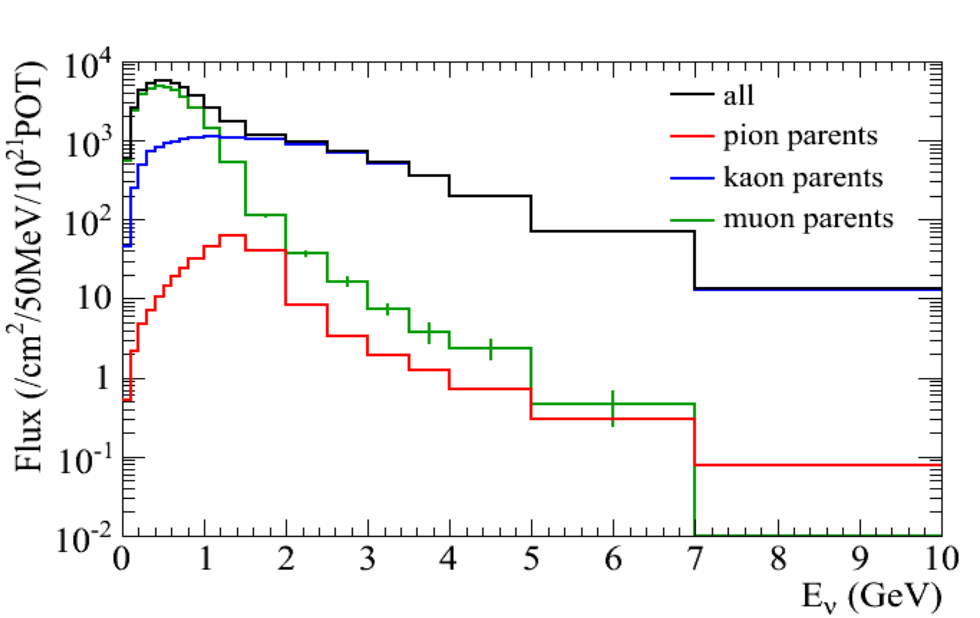
NA61 Hadron production Constraint

External cross section data

Near detector constraint

Analysis Strategy : Flux





- Full covariance matrix for ND280 and SK
- Used in flux and cross section fits.

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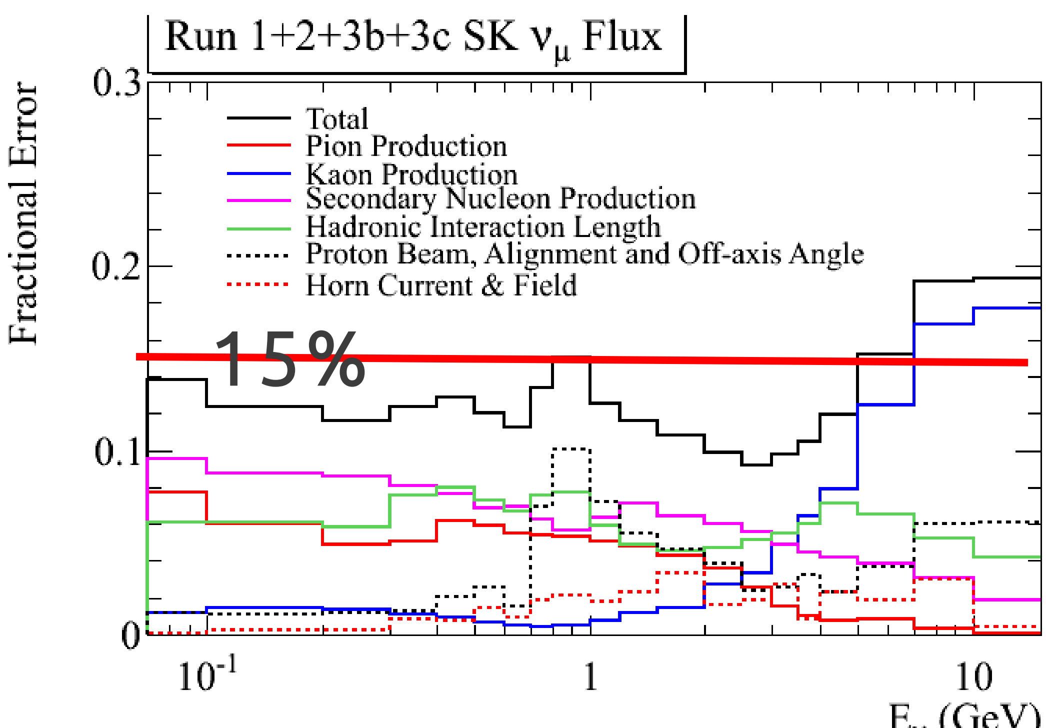
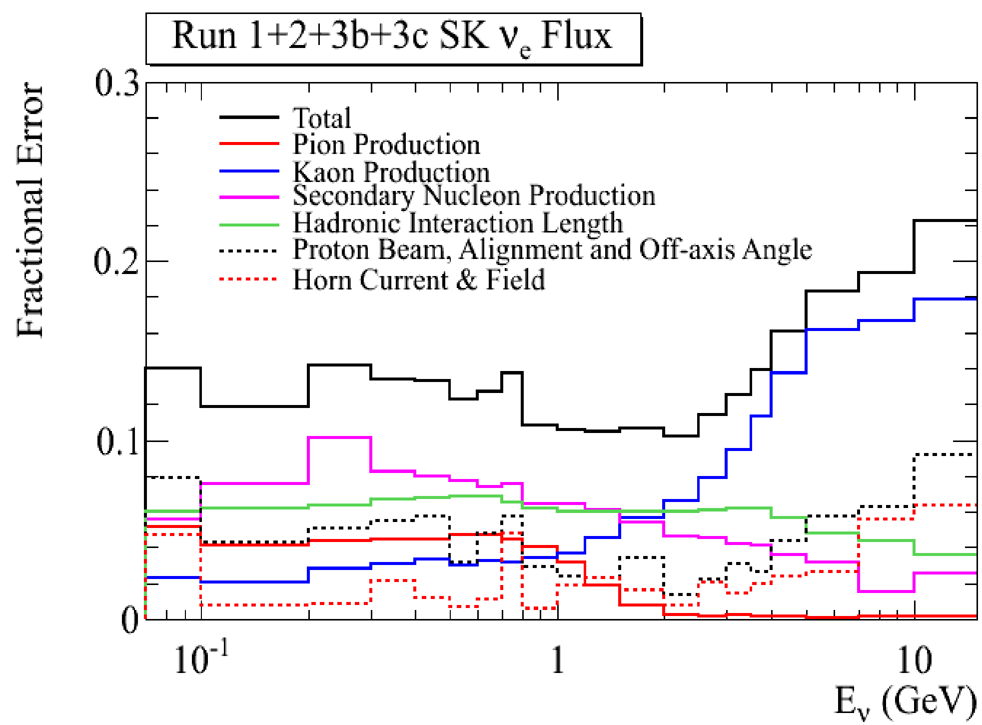
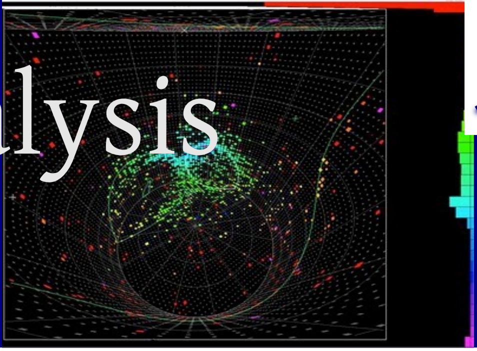


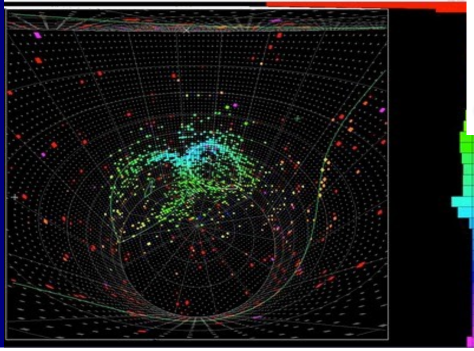


Far Detector Oscillation Analysis Improvements



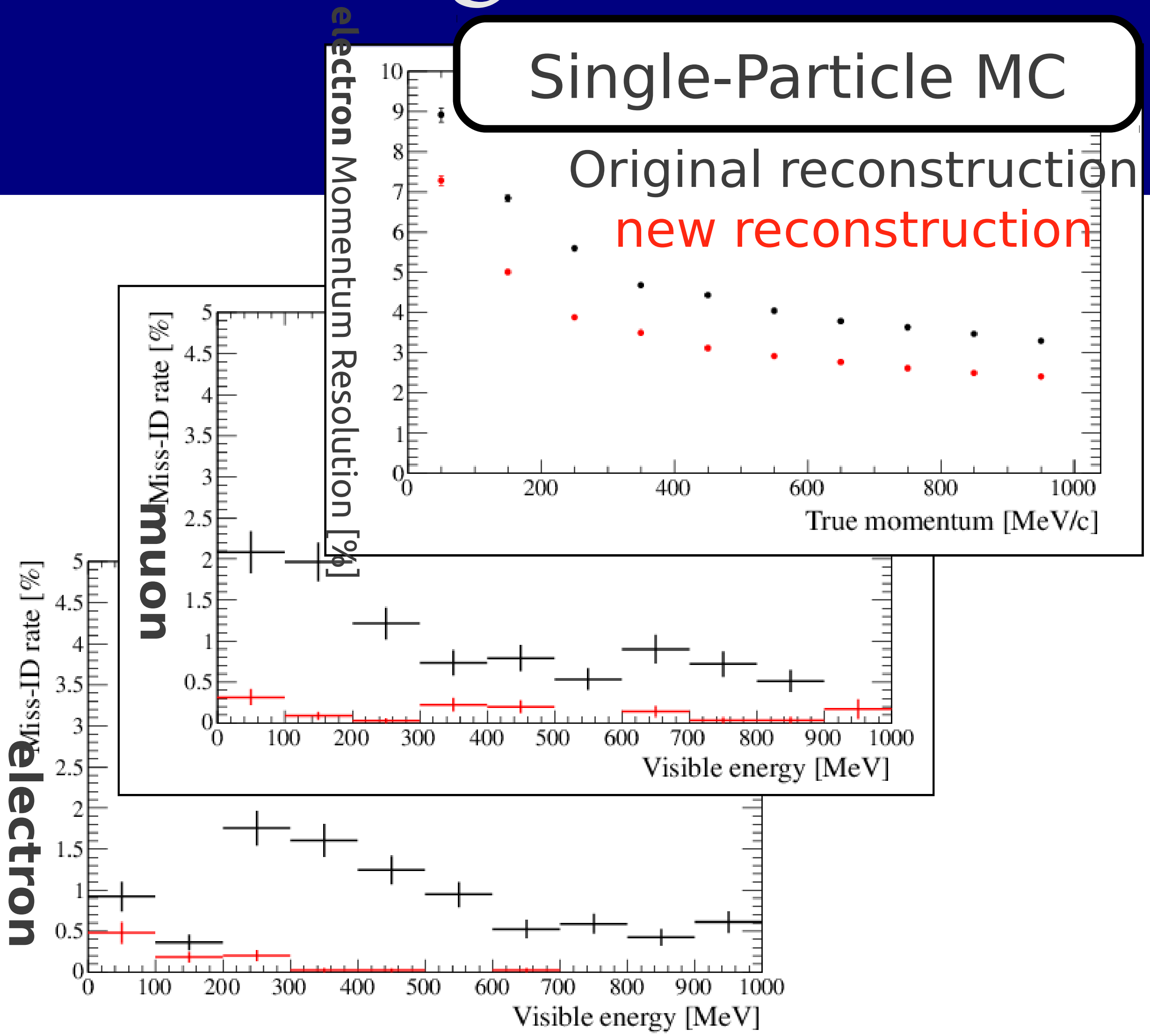
- The strength of T2K thus far has been relying on well-established event reconstruction tools at the far detector
  - After 15 years of operation, is there still room for improvement?
- 2012 T2K Signal/background ratio **2.7** (for $\sin^2 2\theta_{13}=0.1$)
  - Significant gains in ν_e appearance sensitivity from any additional background reduction
- 2012 Total background = **3.22 ± 0.43 events**
  - Beam ν_e background = **1.56 ± 0.20 events** (irreducible)
  - Neutral current (mostly π^0) = **1.26 ± 0.35 events** (reducible?)

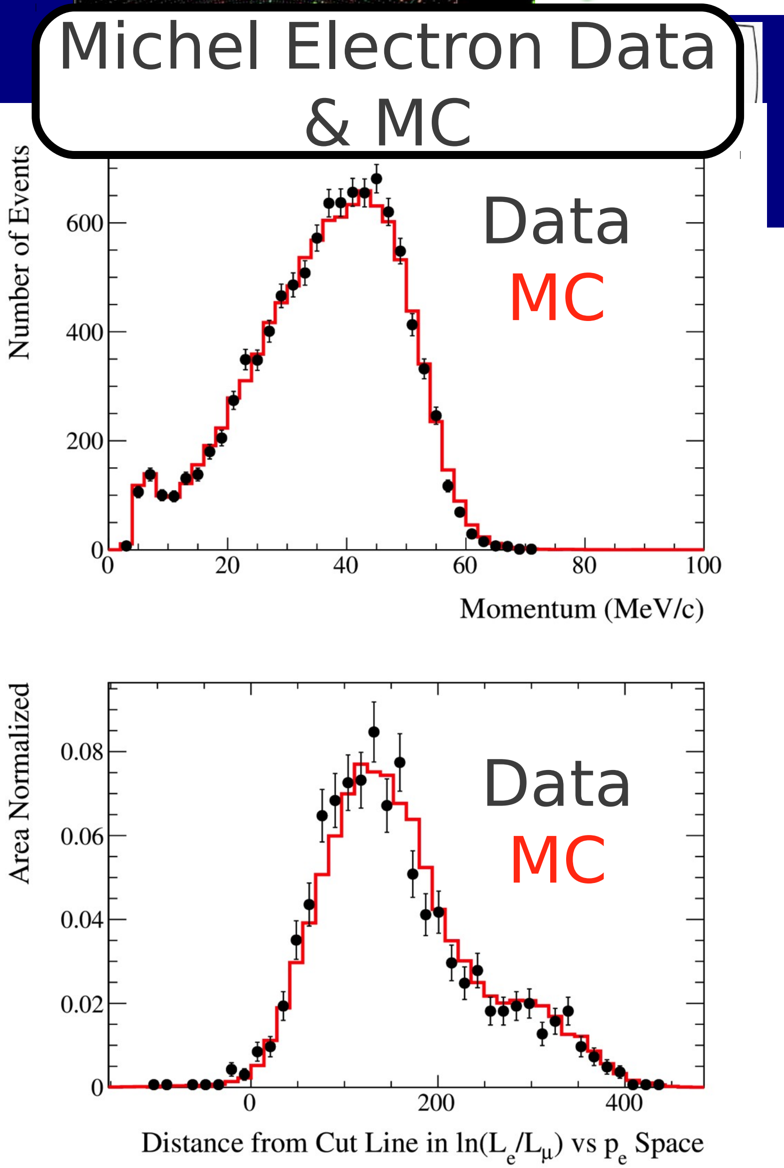
A New Event Reconstruction Algorithm for the far detector



- For each far detector neutrino event we have, for every hit PMT
  - A measured charge
  - A measured time
- For a given event topology hypothesis, it is possible to produce a charge and time PDF for each PMT
  - Main challenge is to predict the number of photons at the PMT (predicted charge, μ -- see next slide)
  - Based on the algorithm used by MiniBooNE (NIM A608, 206 (2009))
- Framework can handle any number of reconstructed tracks
  - Same fit machinery used for all event topologies (e.g. e^- and π^0)
- Event hypotheses are distinguished by comparing best-fit likelihoods
  - electron vs muon
  - 1-ring vs 2-ring vs 3-ring ...

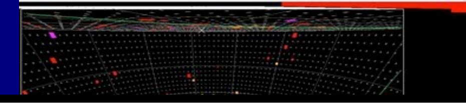
One-Ring-Fit Performance



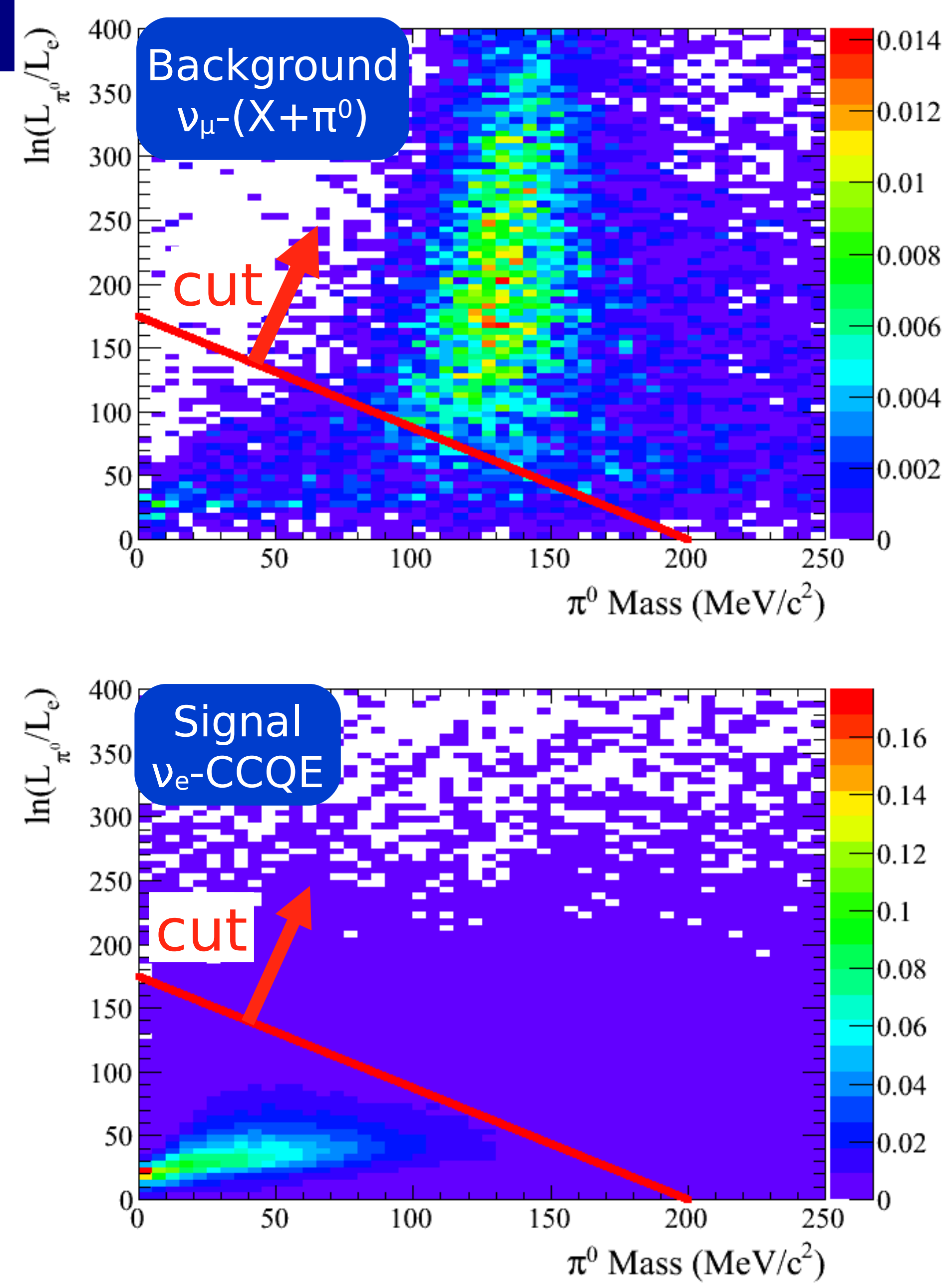


- Significantly better particle ID and momentum reconstruction than previous far detector reconstruction
- Good data/MC agreement in Michel electron sample

Enhanced π^0 Rejection

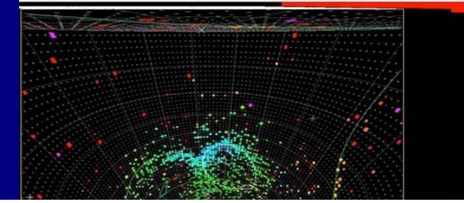


Likelihood Ratio vs π^0 Mass (T2K Monte Carlo)



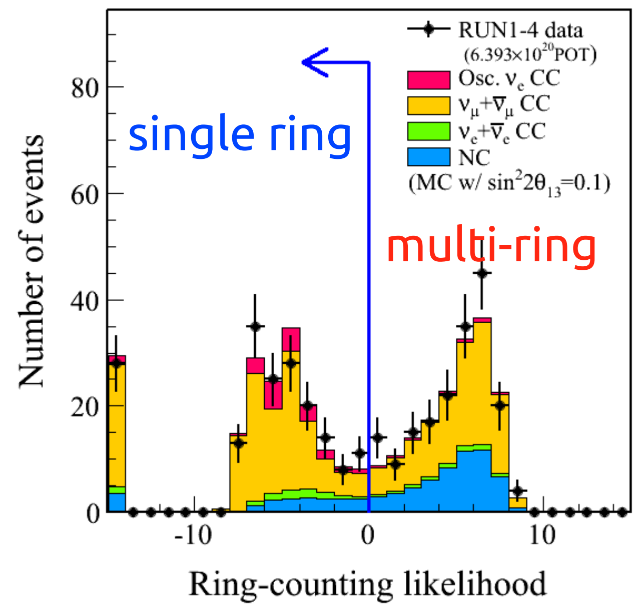
- New algorithm can also use the best-fit **likelihood ratio** to distinguish e^- from π^0
- 2D cut **removes 70% of the remaining π^0 background** allowed by old algorithm for the same signal efficiency
  - Beam ν_e background does not change significantly
- Total background is reduced by 27%

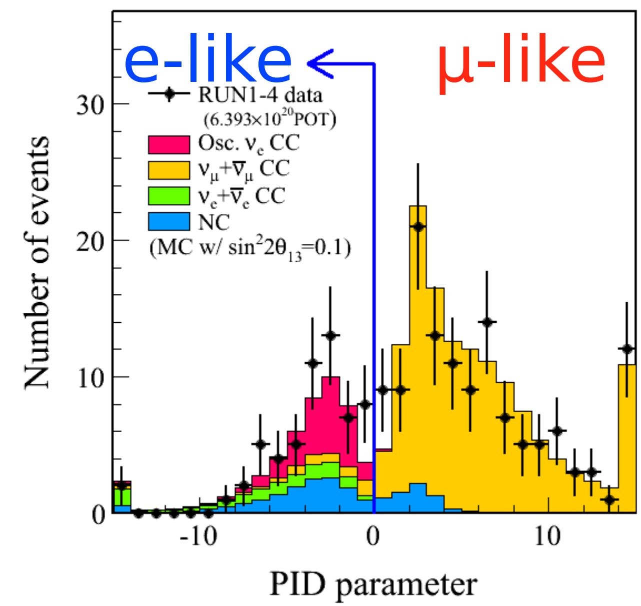
T2K ν_e Event Selection

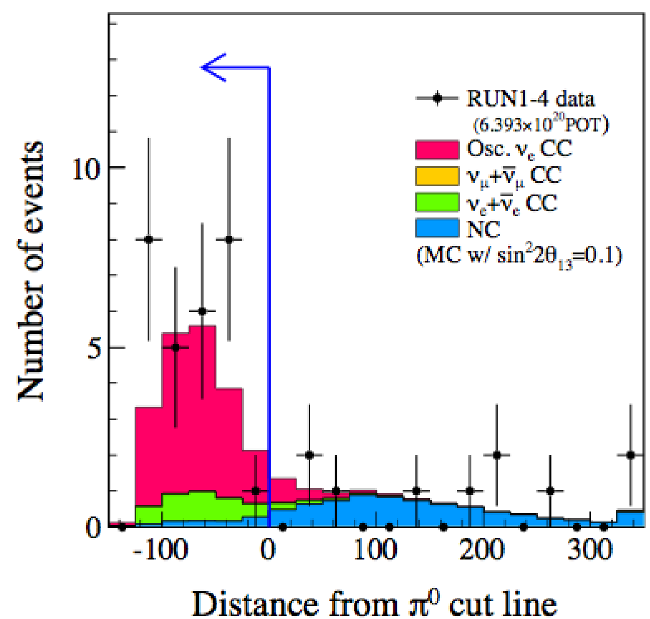


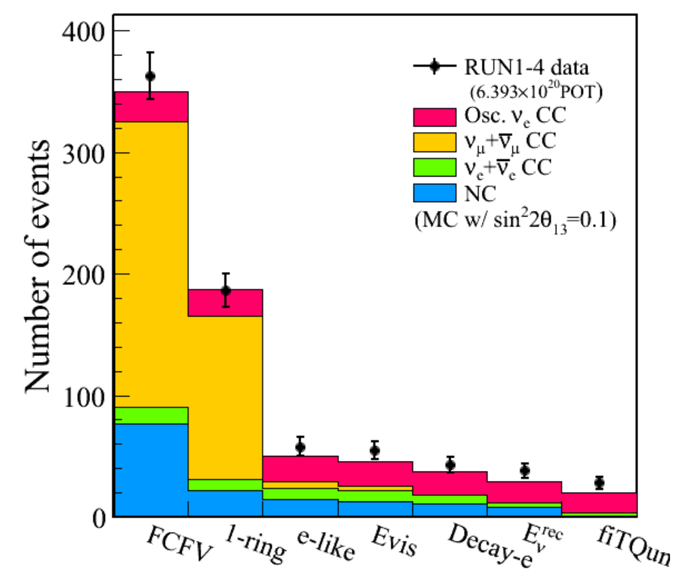
ν_e Selection Cuts

- # veto hits < 16
- Fid. Vol. = 200 cm
- # of rings = 1
- Ring is e-like
- $E_{visible}$ > 100 MeV
- no Michel electrons
- fiTQun π^0 cut
- 0 < E_ν < 1250 MeV

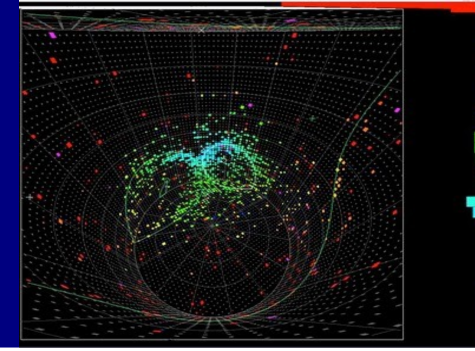


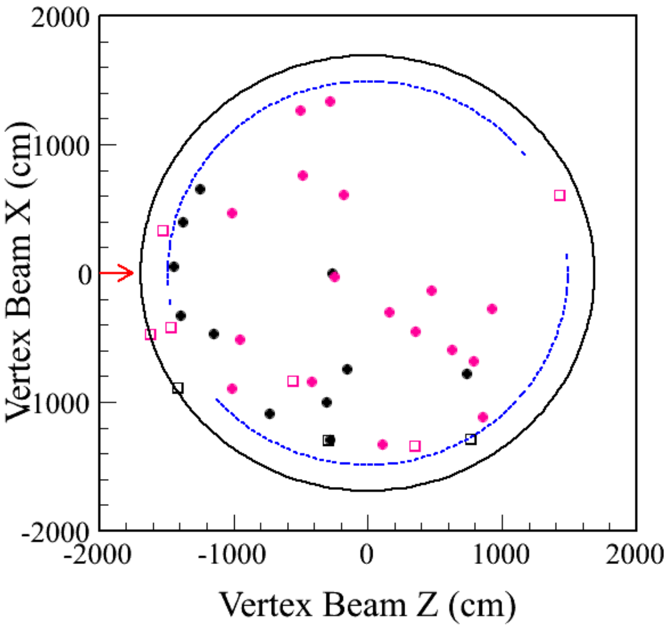


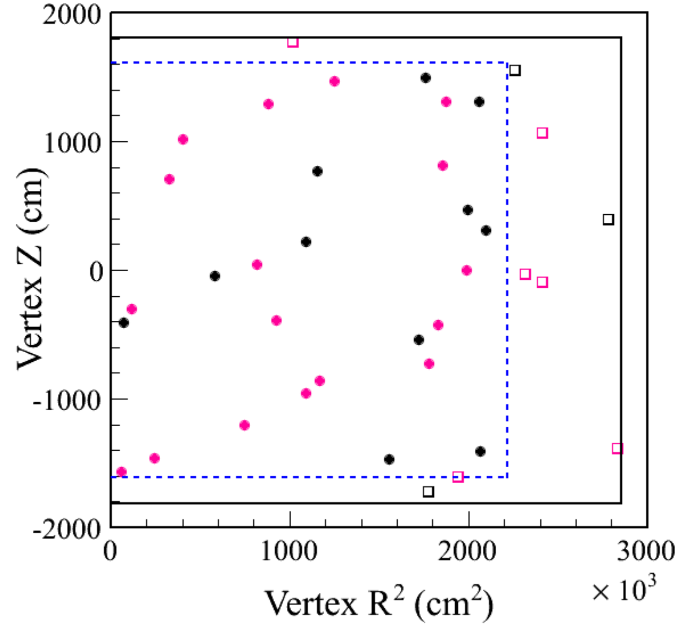


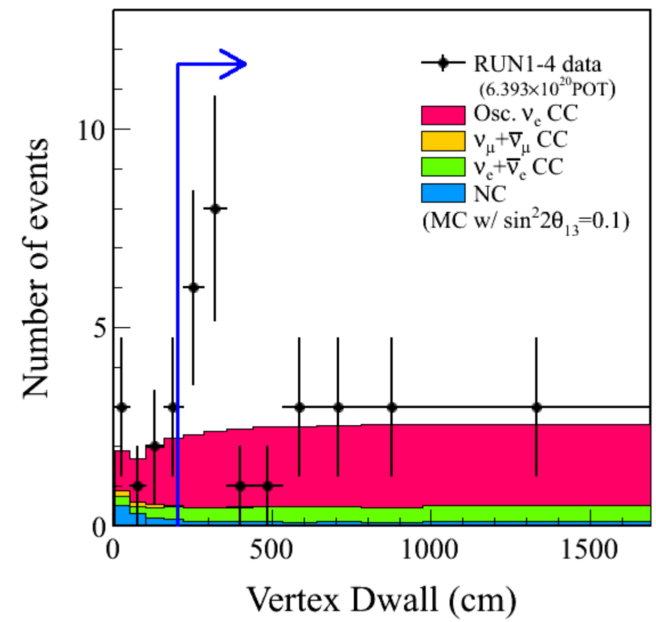


Far Detector ν_e Vertex Distribution





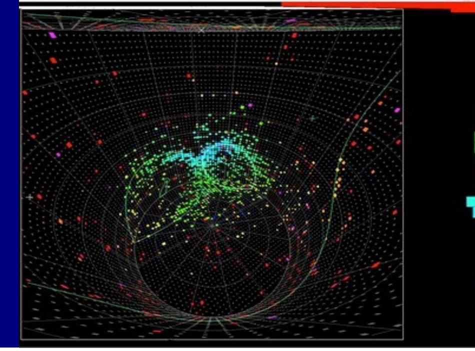


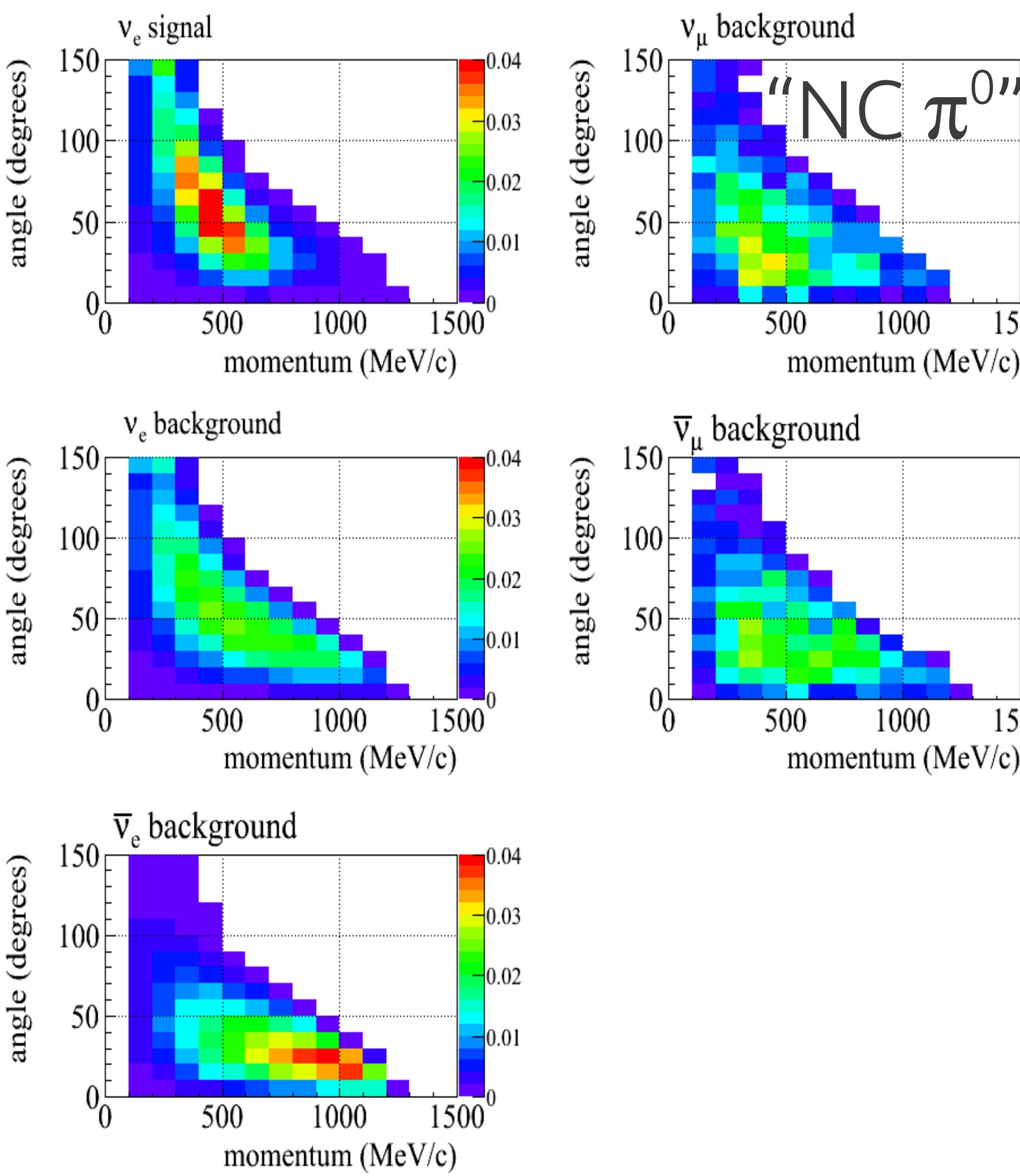


	RUN1+2+3	RUN4	RUN1+2+3+4
Dwall	34.4%	54.7%	20.9%
Fromwall beam$_{\parallel}$	6.04%	85.6%	8.93%
$R^2 + Z$	32.4%	98.1%	64.5%

With increased statistics, the p-values for the test distributions have increased

θ_{13} Analysis





4.64 ± 0.53 background events

20.4 ± 1.8 events expected

For $\sin^2 2\theta_{13}=0.1$, $\sin^2 2\theta_{23}=1$, $\delta_{CP}=0$, and normal mass hierarchy

5.5σ sensitivity to exclude $\theta_{13} = 0$

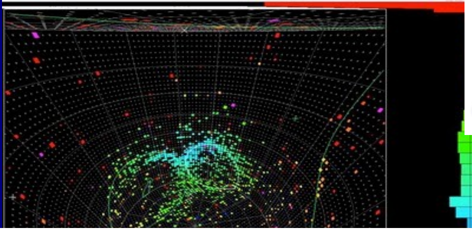
Three analyses:

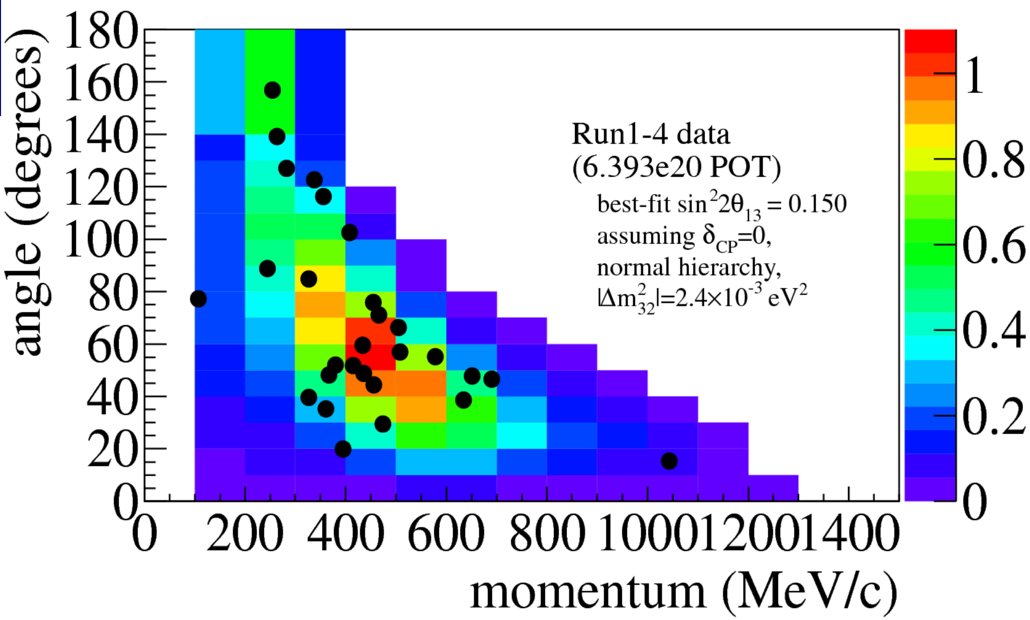
I. Likelihood fit of rate and (p_e, θ_e)

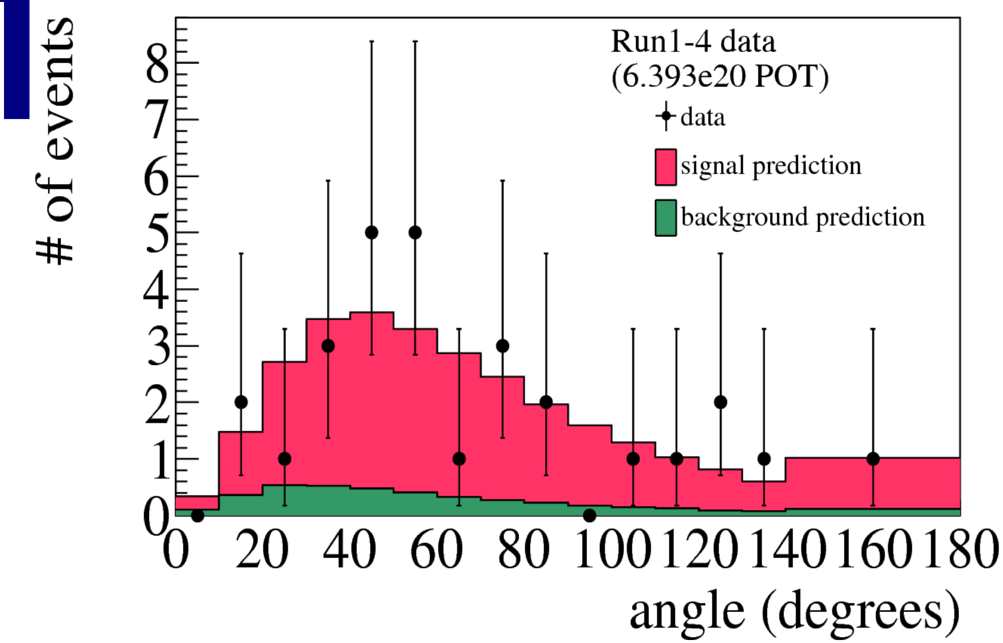
II. Likelihood fit of rate and reconstructed E_ν

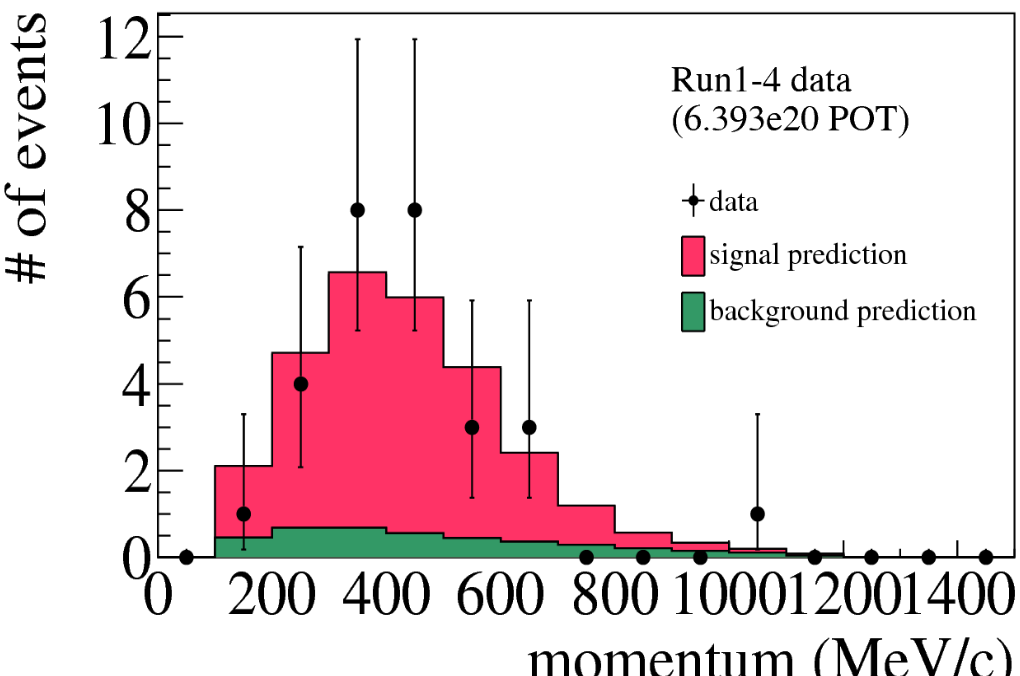
III. Rate only

θ_{13} Analysis Results









Assuming $\delta_{CP}=0$, normal hierarchy, $|\Delta m_{32}{}^2|=2.4\times10\text{-}3\ eV^2$, $\sin^2 2\theta_{23}=1$

90% allowed region:

$$0.097 < \sin^2 2\theta_{13} < 0.218$$

ν_e Appearance Results

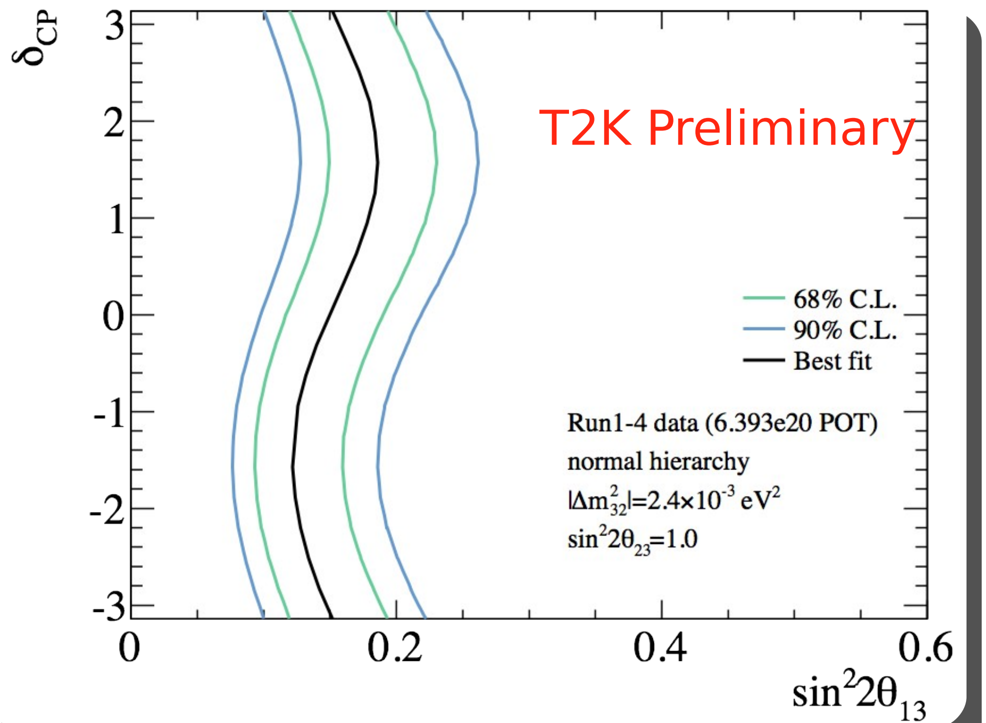
- **Observed 28 events** (expected 20.4 ± 1.8 for $\sin^2 2\theta_{13}$=0.1)

- Comparing the best p-θ fit likelihood to null hypothesis gives:

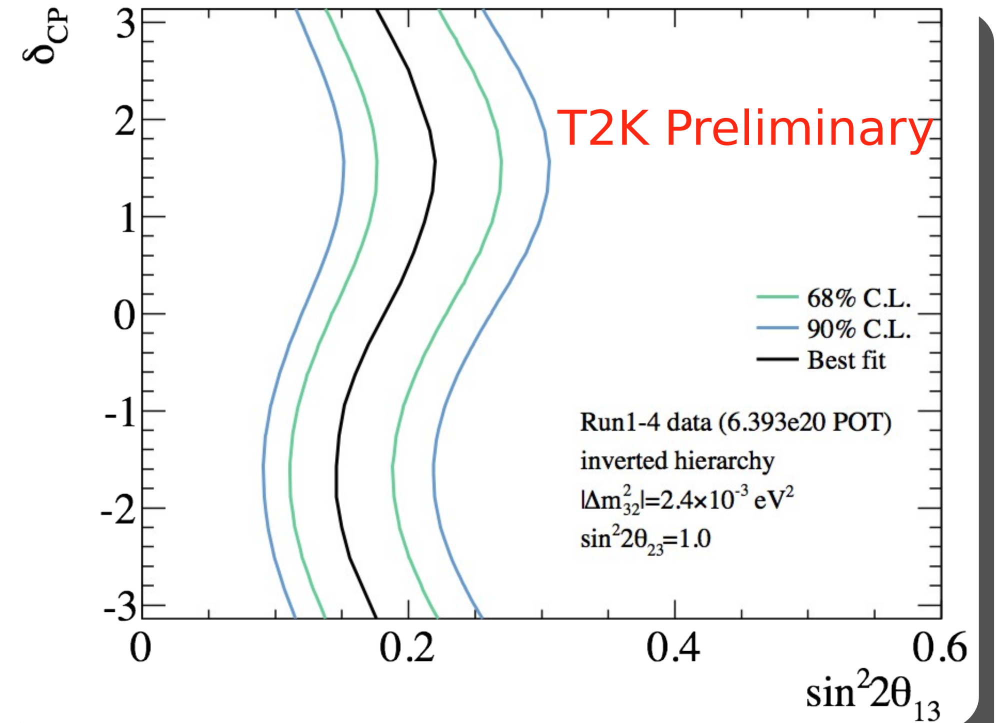
7.5σ significance for non-zero θ_{13}

(For $\sin^2 2\theta_{23}$=1, δ_{CP}=0, and normal mass hierarchy)

T2K δ_{CP} vs $\sin^2 2\theta_{13}$ (Normal Hierarchy)



T2K δ_{CP} vs $\sin^2 2\theta_{13}$ (Inverted Hierarchy)

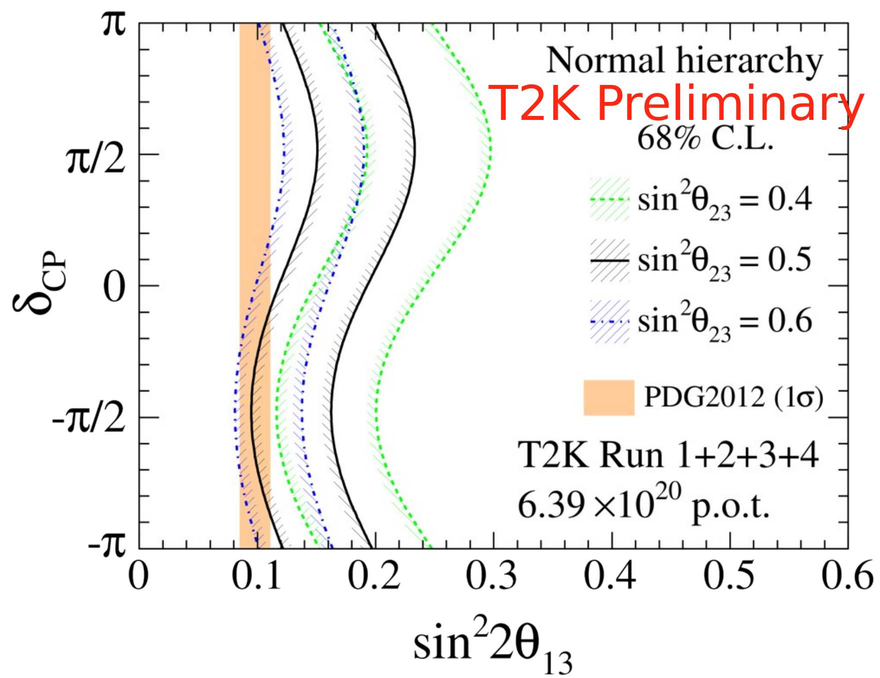


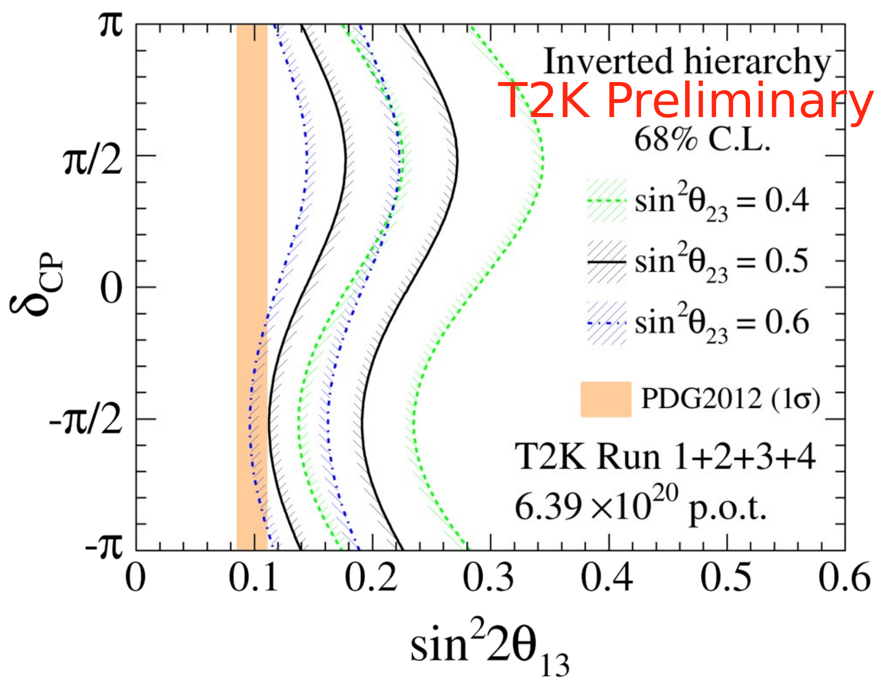
Note: These are 1D contours for various values of δ_{CP}, not 2D contours

First observation (>5σ) of an explicit ν appearance channel

Effect of θ_{23} Uncertainty

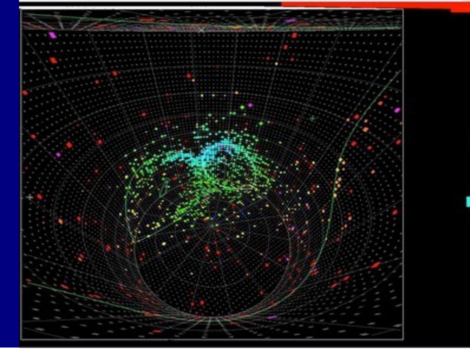
- ν_e appearance probability also depends on the value of θ_{23}
- If θ_{23} is fixed at values near the edge of the current allowed region, the fit contours shift
- Future improved measurements of θ_{23} will be important to extract information about other oscillation parameters (including δ_{CP}) in long-baseline experiments
  - A T2K combined ν_e+ν_μ analysis is underway

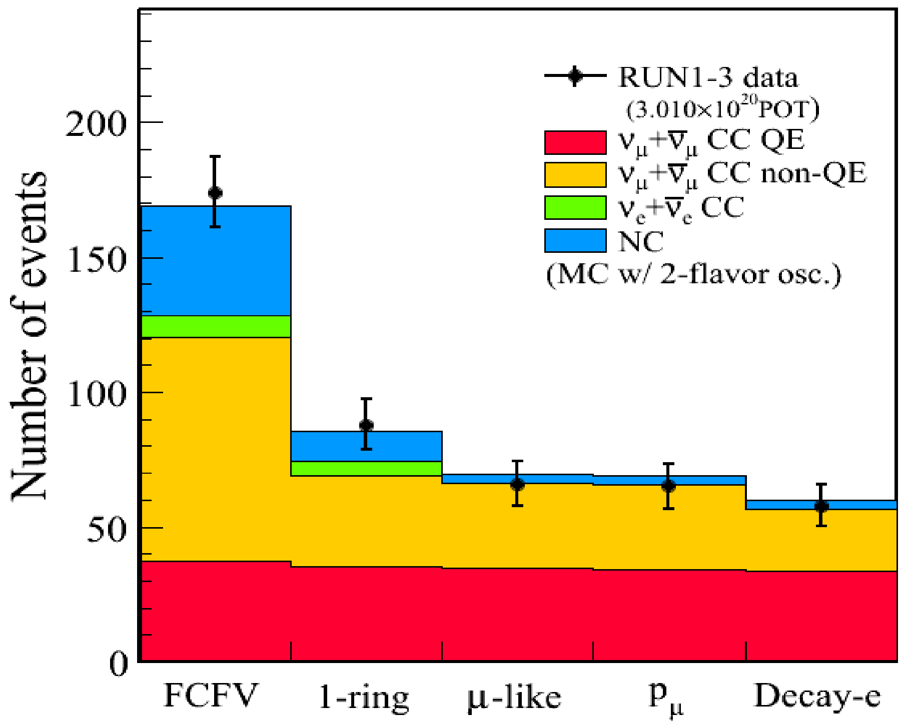




Note: these are 1D contours for various values of δ_{CP}, not 2D contours

ν_μ Selection



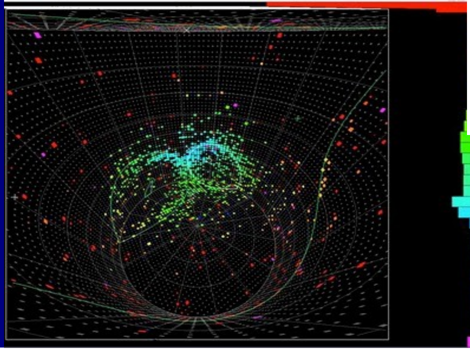


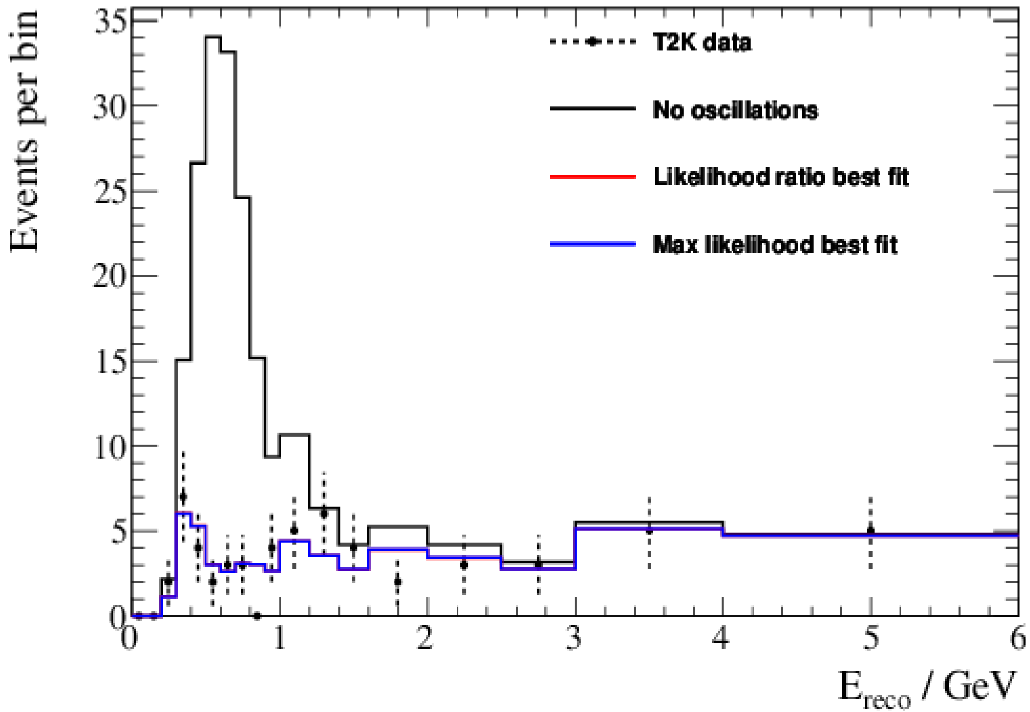
- Fully Contained in ID
- One muon-like ring
- p_μ > 200 MeV
- # decay electron <= 1

Observed : 58 events

Expected : 207 event without oscillations @ 3.01×10^{20} POT

ν_μ Disappearance





- Best fit parameters:

$$\sin^2(2\theta_{23}) = 1.0$$

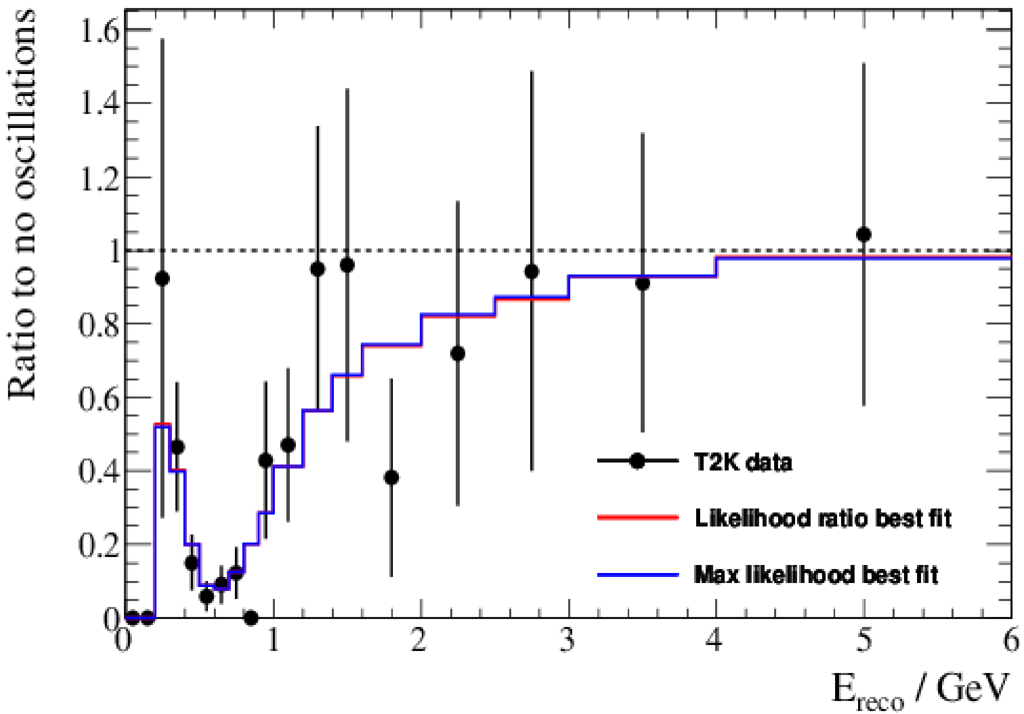
$$(A1)\ \Delta m^2_{23} = 2.45\times10^{-3}\,eV^2$$

$$(A2)\ \Delta m^2_{23} = 2.44\times10^{-3}\,eV^2$$

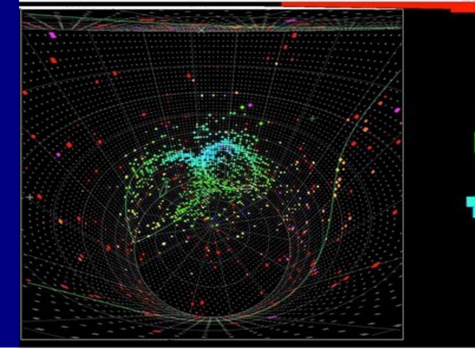
Observed : 58 events

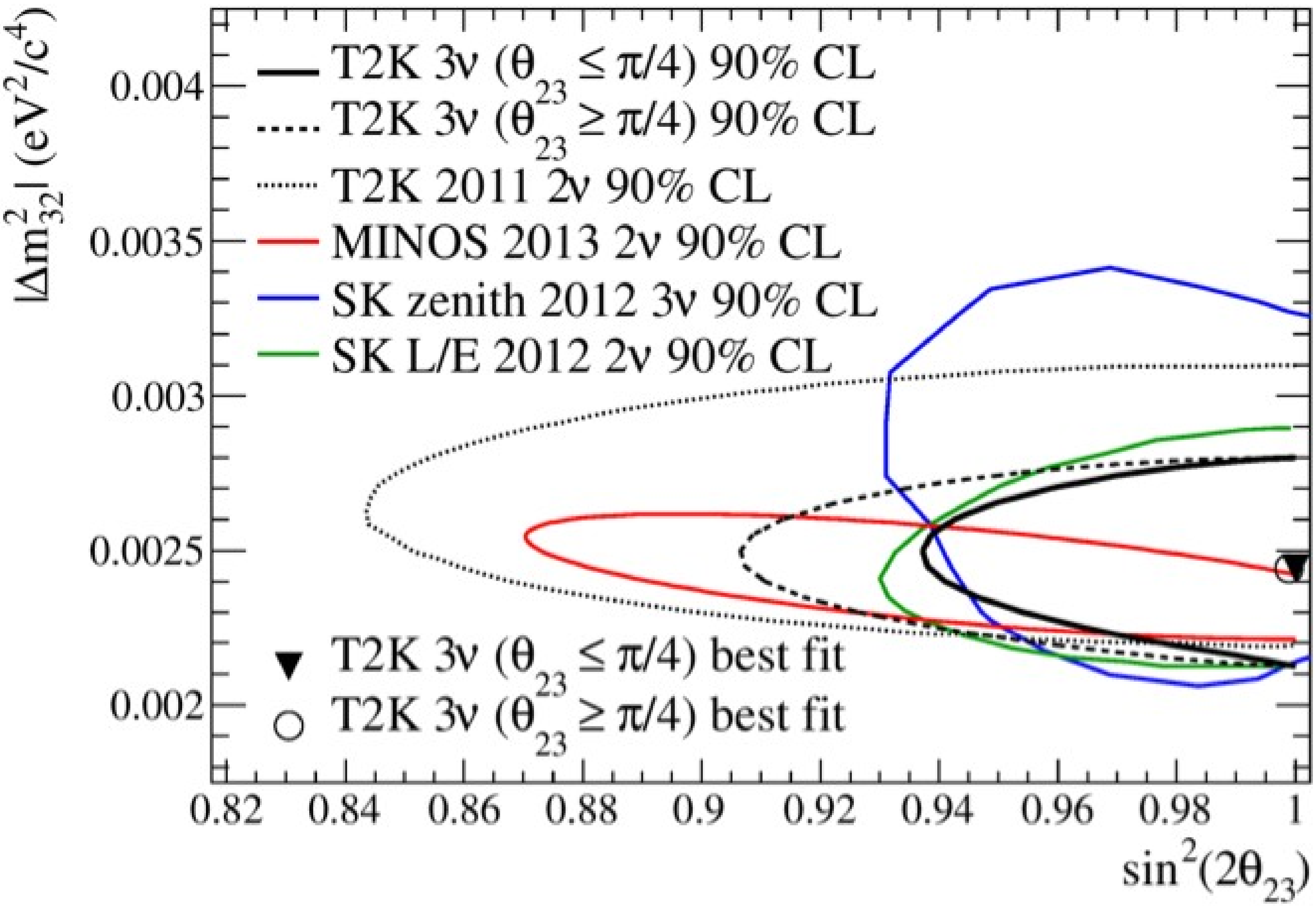
Expected : 207 events without oscillations

@ 3.01 x 10^{20} POT

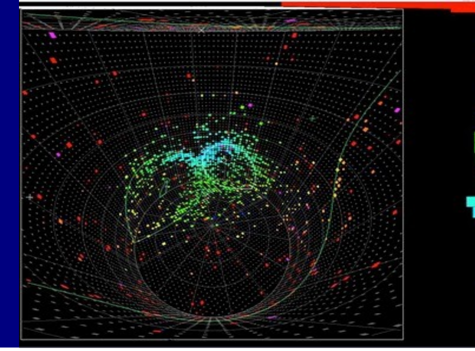


ν_μ Disappearance



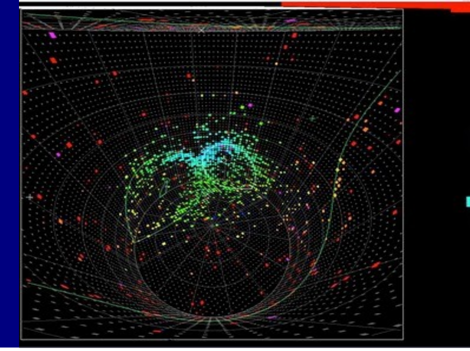


T2K Program

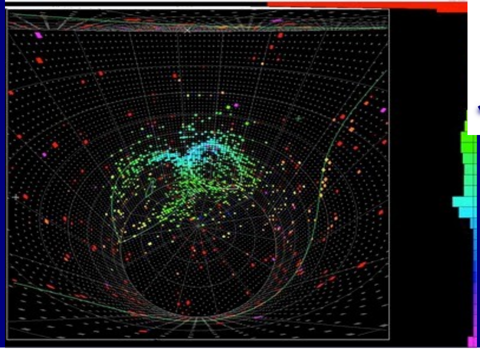


- Precision measurement of appearance
  - Compare with reactor results
  - Try to see first hint on CPV and mass hierarchy
  - Measurement of Δm_{13}^2
- Precision measurement of disappearance
  - θ_{23}, Δm_{23}^2
  - Whether maximal mixing or not?
  - Important for probing CPV
- Sterile neutrino searches
- Pursue possibility of anti-nu measurements
- Various cross section measurements at near detector

Summary

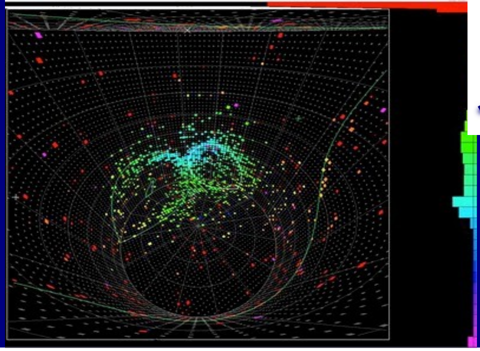


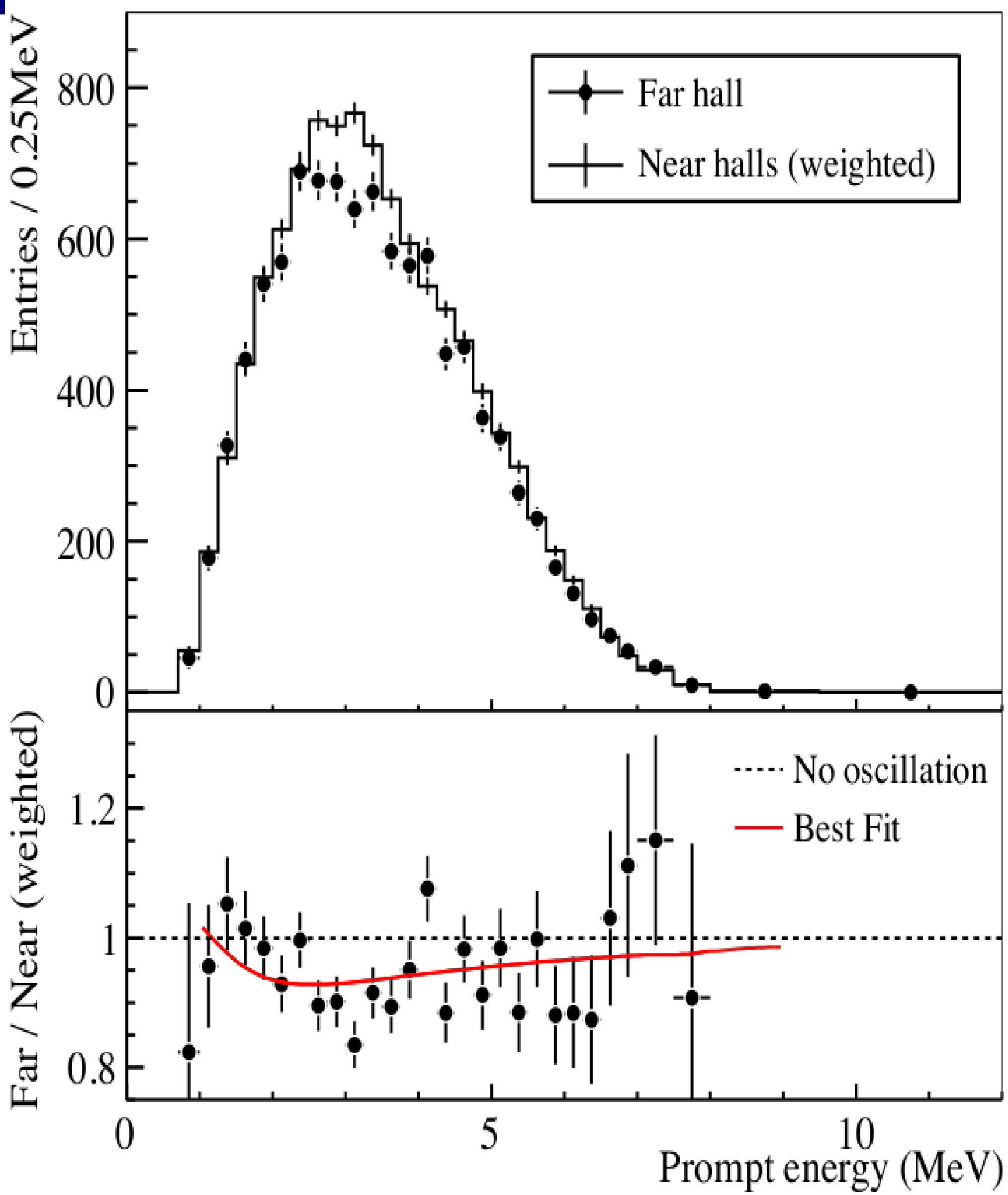
- J-PARC accelerator has achieved stable 220kW running for most of run 4
- With only 8% of planned POT we have presented :
  - Direct evidence for ν_e appearance
    - $U_{e3} = 0$ rejected at 7.5 σ ($\sin^2 2\theta_{23}$=1)
      - NH: $\sin^2 2\theta_{13} = 0.150^{+0.039}_{-0.034}$
      - IH: $\sin^2 2\theta_{13} = 0.182^{+0.046}_{-0.040}$
      - Complementary to reactor results
  - Competitive measurement of disappearance parameters
- Medium/long term run plans under study



Backups

θ_{13} Results : Reactors





Daya Bay

$$\sin^2(2\theta_{13}) = 0.092 \pm 0.016\,(stat) \pm 0.005\,(sys)$$

Reno

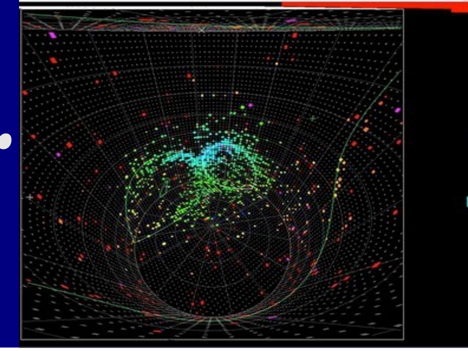
$$\sin^2(2\theta_{13}) = 0.113 \pm 0.013\,(stat) \pm 0.019\,(sys)$$

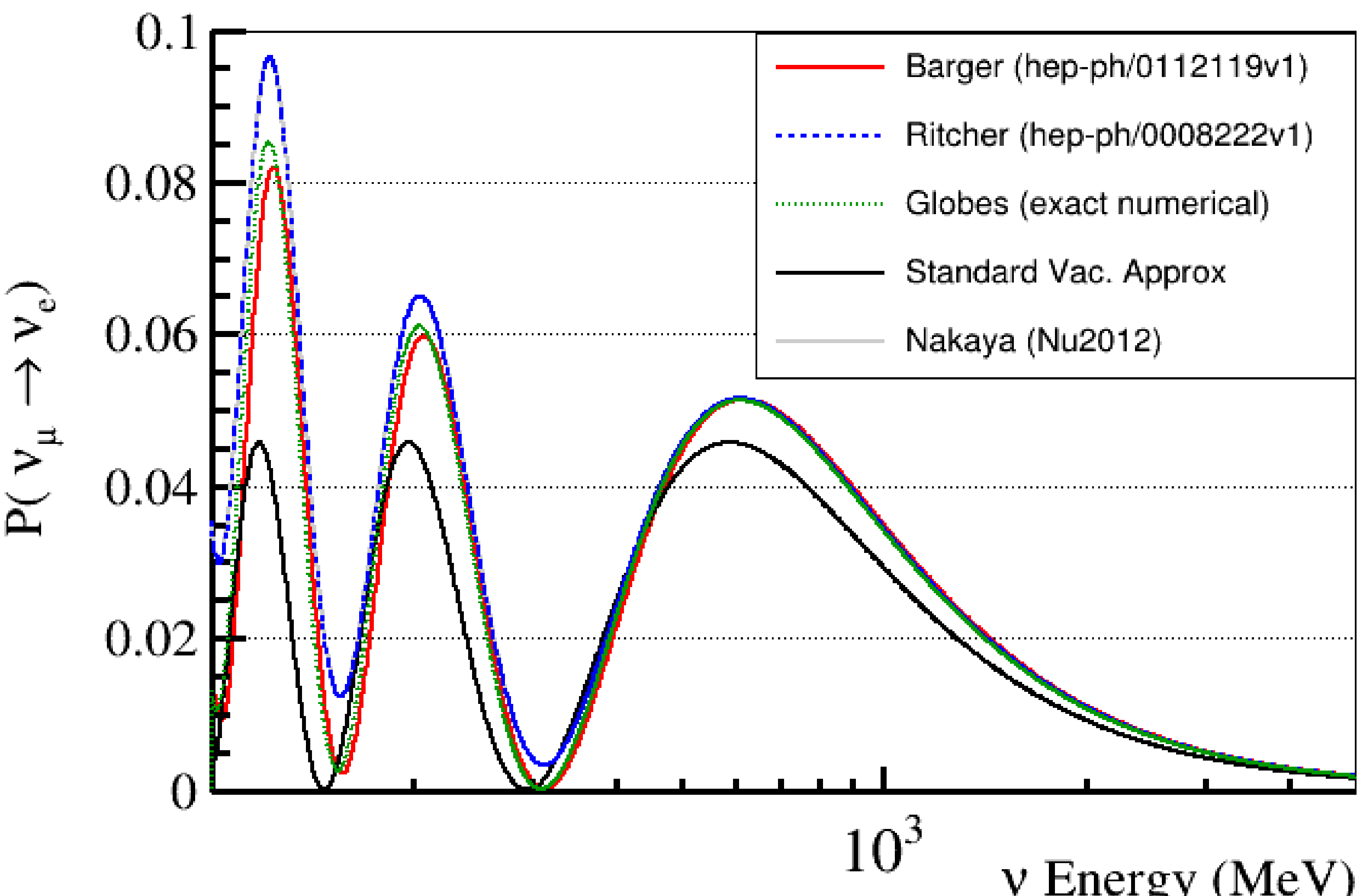
Double CHOOZ

$$\sin^2(2\theta_{13}) = 0.086 \pm 0.041\,(stat) \pm 0.030\,(sys)$$

$\theta_{13} = 0$ excluded at $> 5\,\sigma$

3 flavour oscillation approx. compared to exact soln

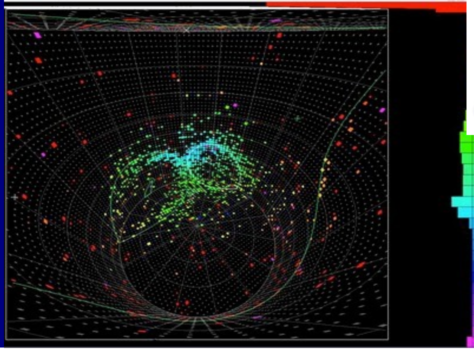


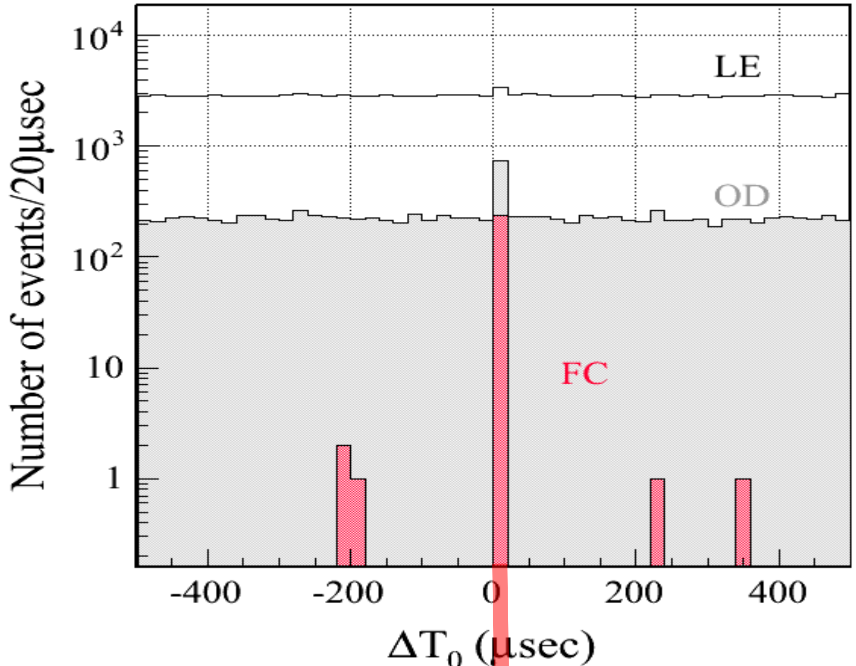


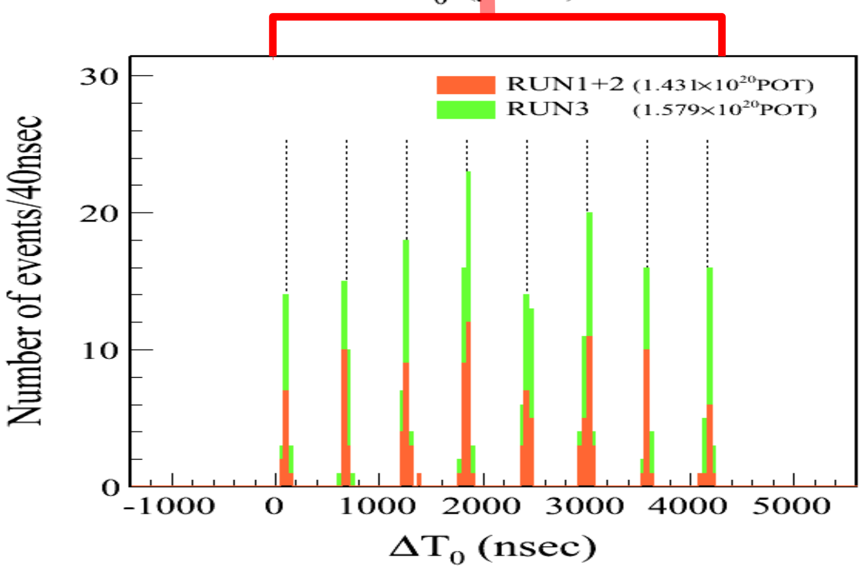
Plot for:
L = 295 km
ρ = 2.6 g/cm^3
Δm_{12} = 7.6x10^5 eV^2
Δm_{23} = 2.4x10^3 eV^2
θ_{12} = 34°
θ_{23} = 45°
θ_{13} = 8.8°
δ = 0, 45°

Some of approximate solutions break down at lower neutrino energy,
But mostly below T2K energy range

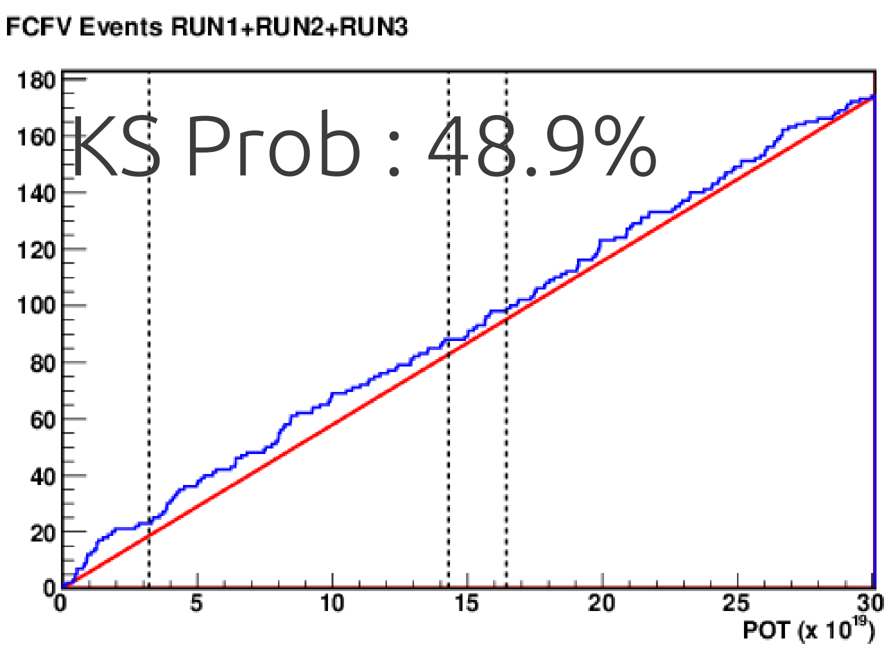
T2K Event Selection



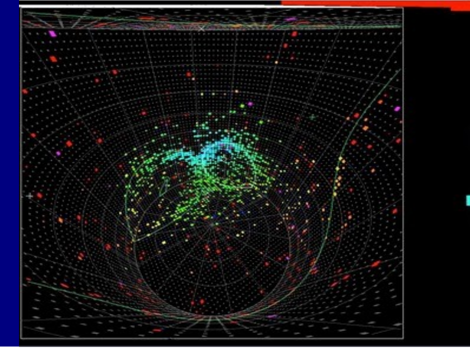




- Time within 500 μs of expected arrival time
- Fully Contained (no OD signal)
- Vertex > 2m from ID wall

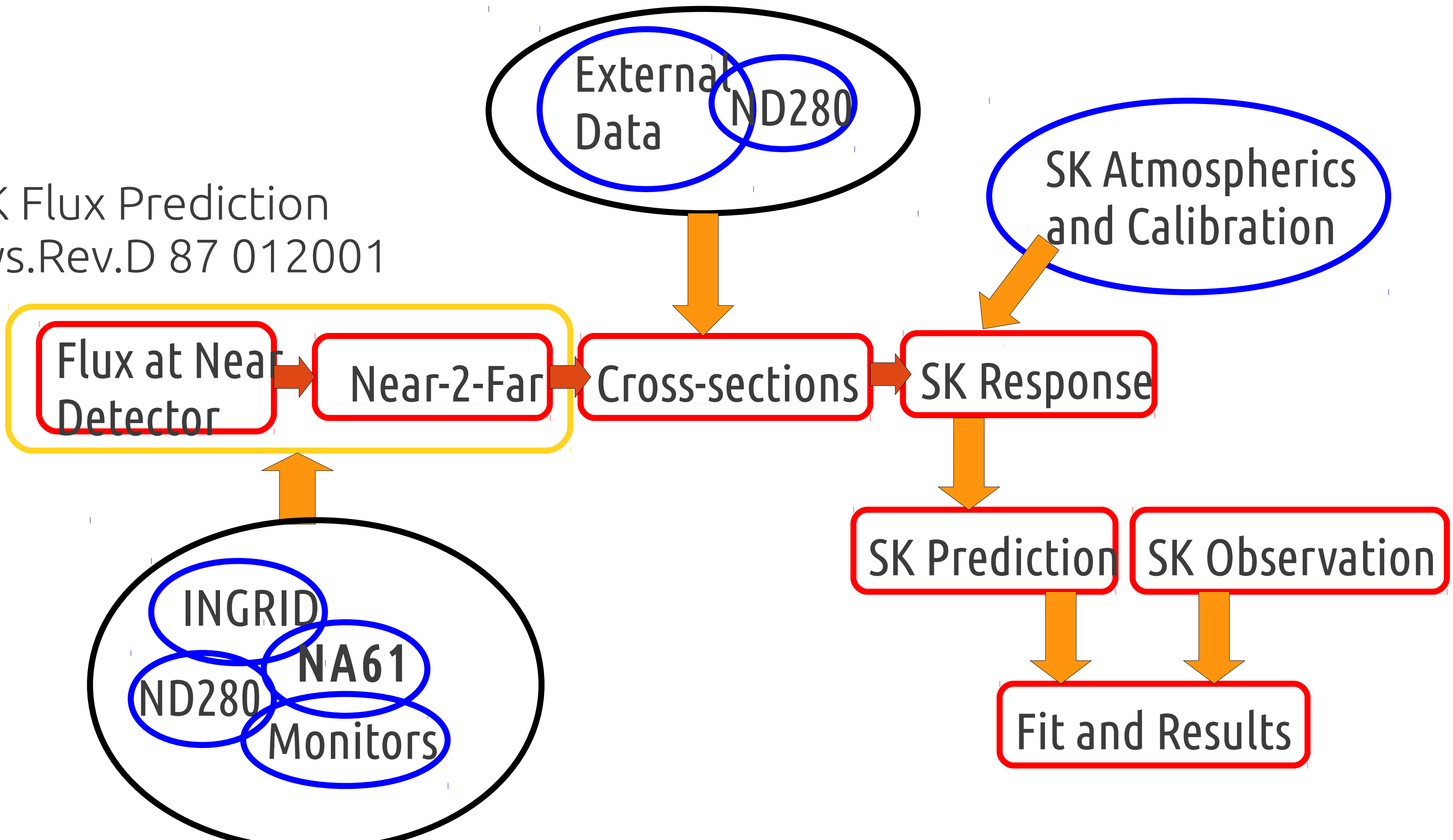


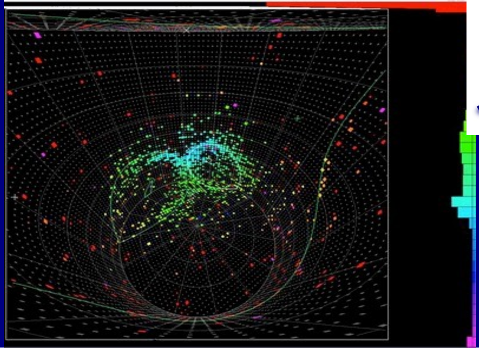
Analysis Strategy



$$N_{SK}^{pred}(\boldsymbol{p}_{\nu,rec}) = \Phi_{SK}^{\exp}(E_{\nu}^{true})\, P_{osc}(E_{\nu}^{true})\, \sigma_{SK}(\boldsymbol{p}_{\nu,rec})\, \epsilon_{SK}(\boldsymbol{p}_{\nu,rec})\; f(\boldsymbol{p}_{\nu,rec}, E_{\nu}^{true})$$

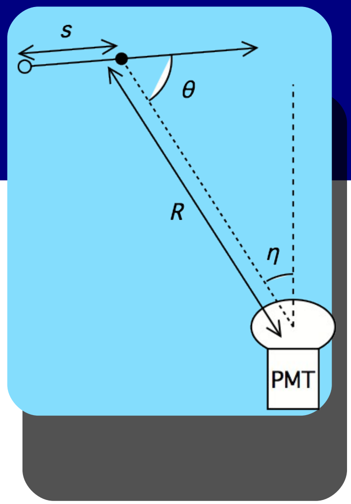
T2K Flux Prediction
Phys.Rev.D 87 012001





New Far Detector Reconstruction Algorithm

Predicted Charge (μ)



$$\mu^{\mathrm{dir}} = \Phi(p)\int ds\,g(s,\cos\theta)\Omega(R)T(R)\epsilon(\eta)$$

Light Yield

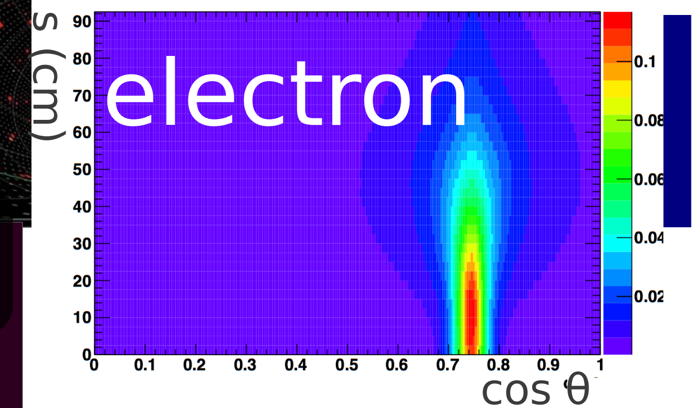
Integral over track length

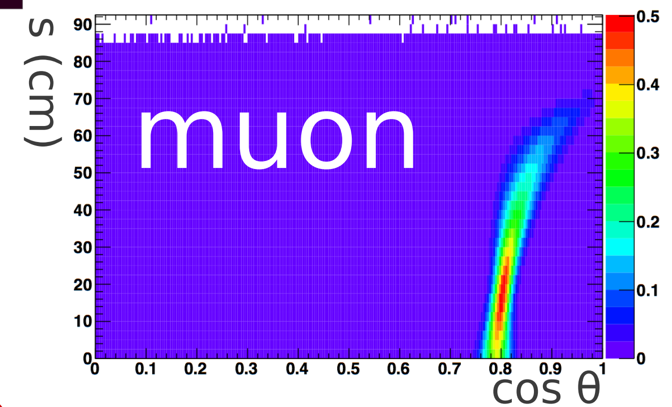
PMT solid angle

Water attenuation

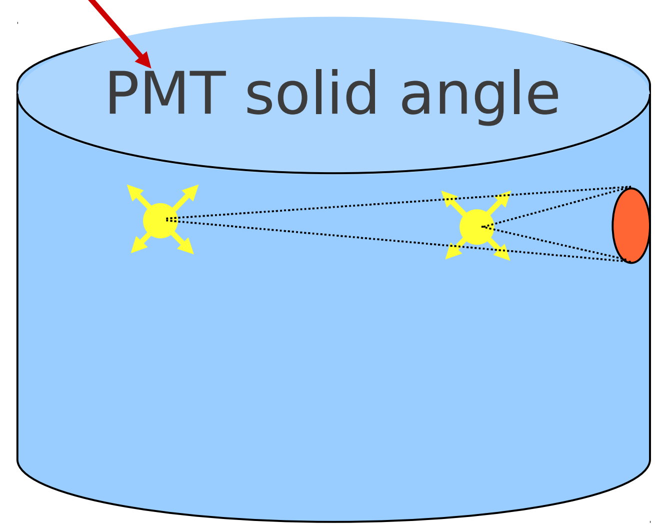
PMT angular response

Cherenkov light emission profile

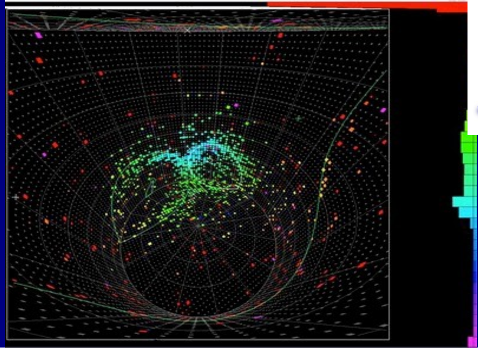




- μ^{dir} is the predicted charge due to "direct light" only (scattered light is handled separately)
- μ is an integral over the length of the track (parameterized by the momentum, p)
- Cherenkov light emission is characterized by g(s,cosθ)
  - These functions must be generated separately for each particle type
  - All particle ID comes from these distributions
- Ω, T, and ε depend on the geometry and detector properties

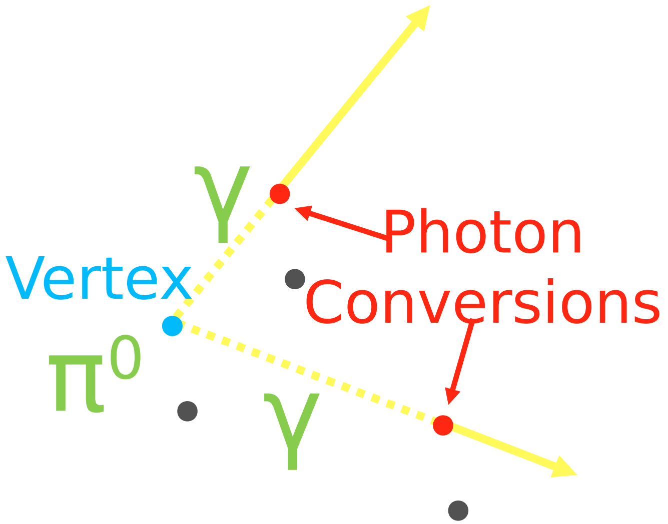


π^0 Fitter



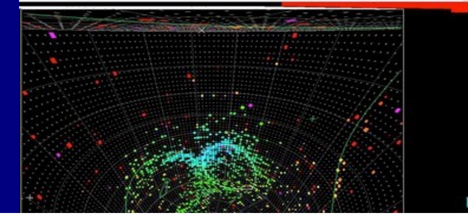
- Assumes two electron-like rings produced at a common vertex

- **12 parameters** (single track fit had 7)
  - Vertex (X, Y, Z, T)
  - Directions (θ_1, φ_1, θ_2, φ_2)
  - Momenta (p_1, p_2)
  - Conversion lengths (c_1, c_2)

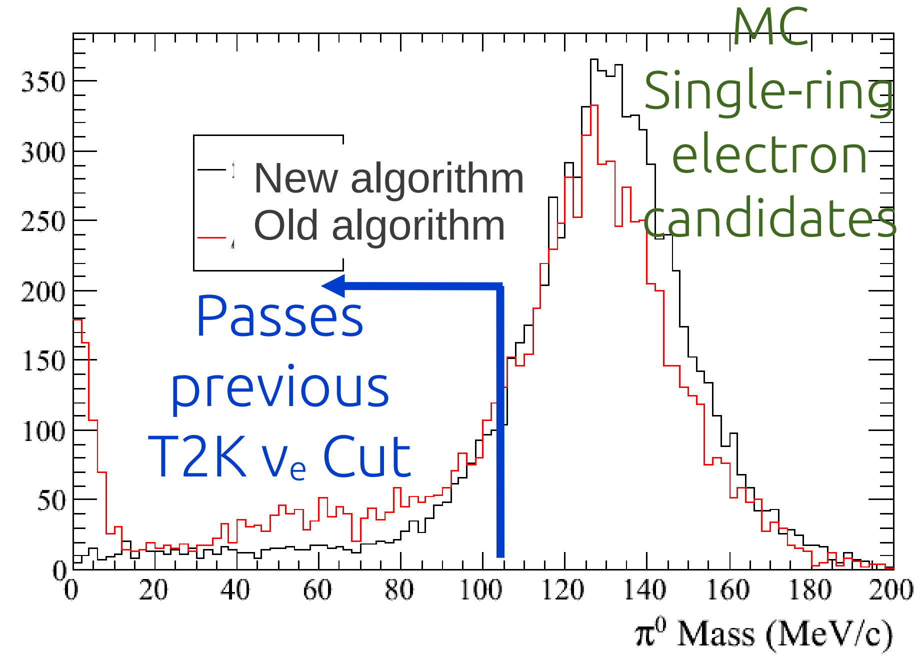


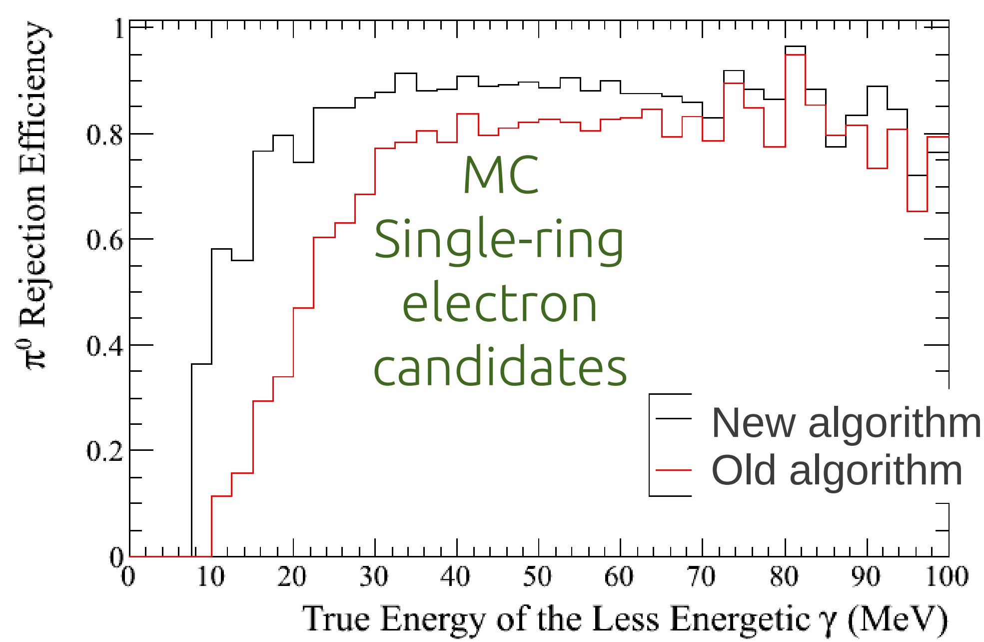
- **All 12 parameters are varied simultaneously**

π^0 Fit Performance

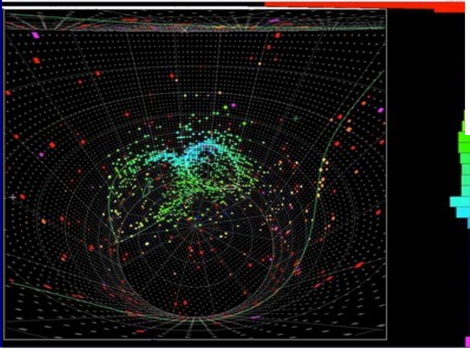


- Previous T2K ν_e appearance cut: **m_{π^0} < 105 MeV/c^2**
- The π^0 mass tail is much smaller for fiTQun
  - Significant spike at zero mass in previous fitting algorithm (**APFit**)
- **Lower plot:** π^0 rejection efficiency vs lower photon energy
  - fiTQun is more sensitive to lower energy photons

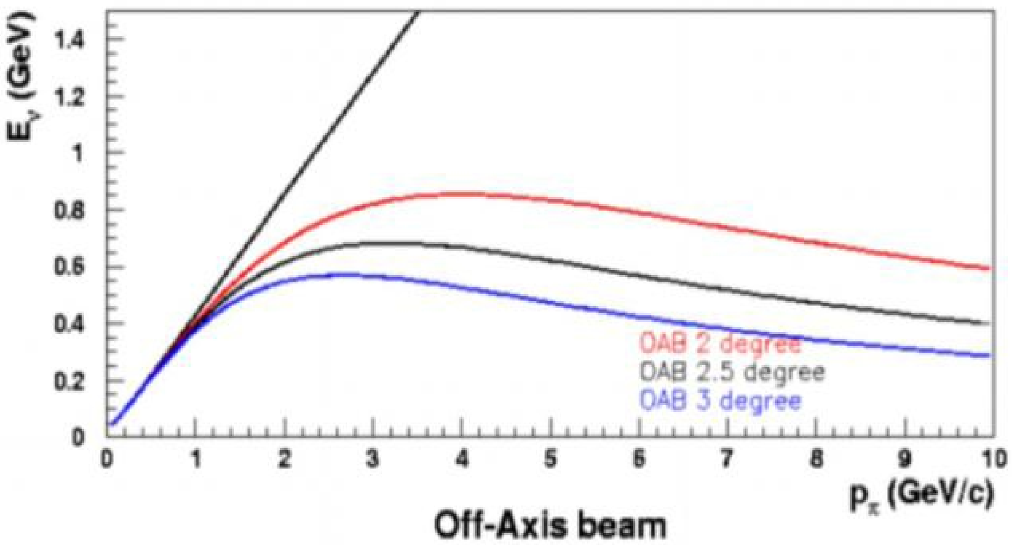


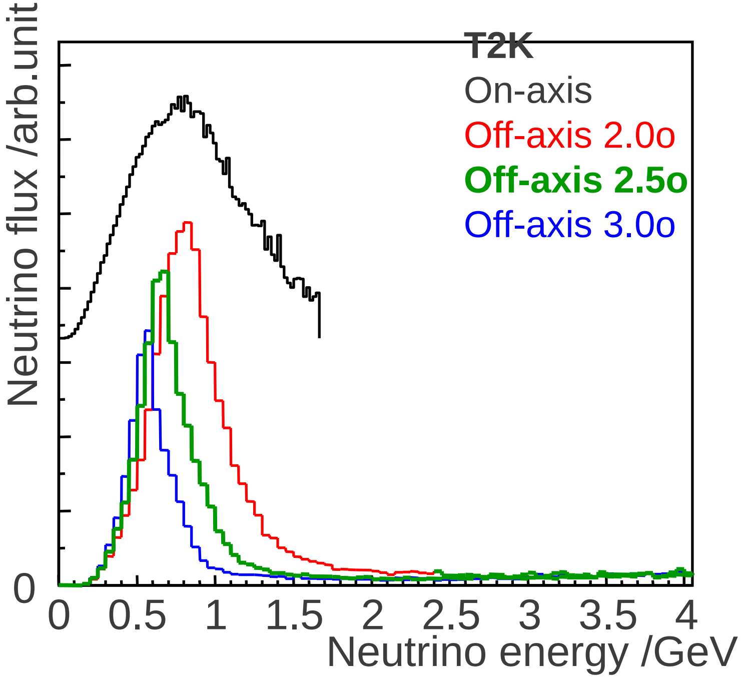


Off-axis Beams



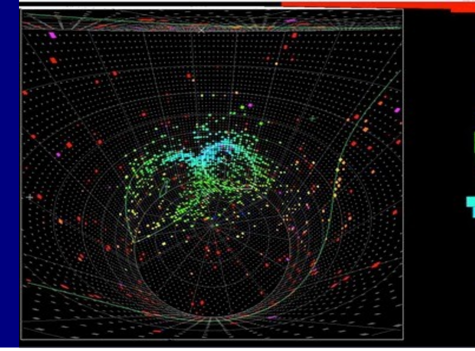
2-Body pion decay kinematics naturally produce a beam that is independent of pion momentum off-axis





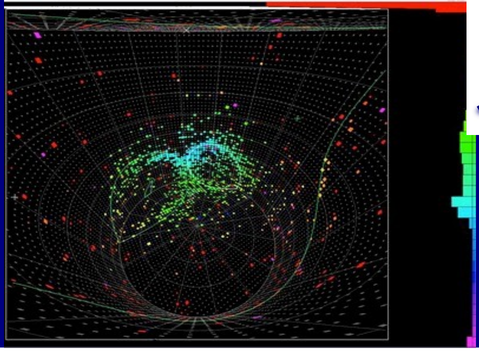
- "Pseudo"-monochromatic
- High energy on-axis tail, which is a background generator, is reduced
- More sensitive to beam angle

Analysis Strategy : Xsec



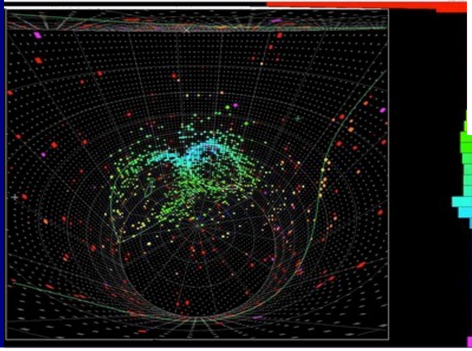
Cross sections modelled by NEUT or GENIE
External constraints provided by MiniBooNE, NOMAD, SciBooNE

QE1 $0 < E\nu < 1.5$ GeV	Normalisation
QE2 $1.5 < E\nu < 3.5$ GeV	Normalisation
QE3 $E\nu < 3.5$ GeV	Normalisation
CC 1π $E\nu < 2.5$ GeV	Normalisation
CC 1π $E\nu > 2.5$ GeV	Normalisation
NC $\pi 0$	Normalisation
M_A(QE)	Shape – Axial Mass QE
M_A(Res)	Shape – Axial Mass Res
pF	Inital State – Fermi momentum
Eb	Initial State – Binding Energy
Spectral Function	Initial State
CC Other	
CC Coherent	

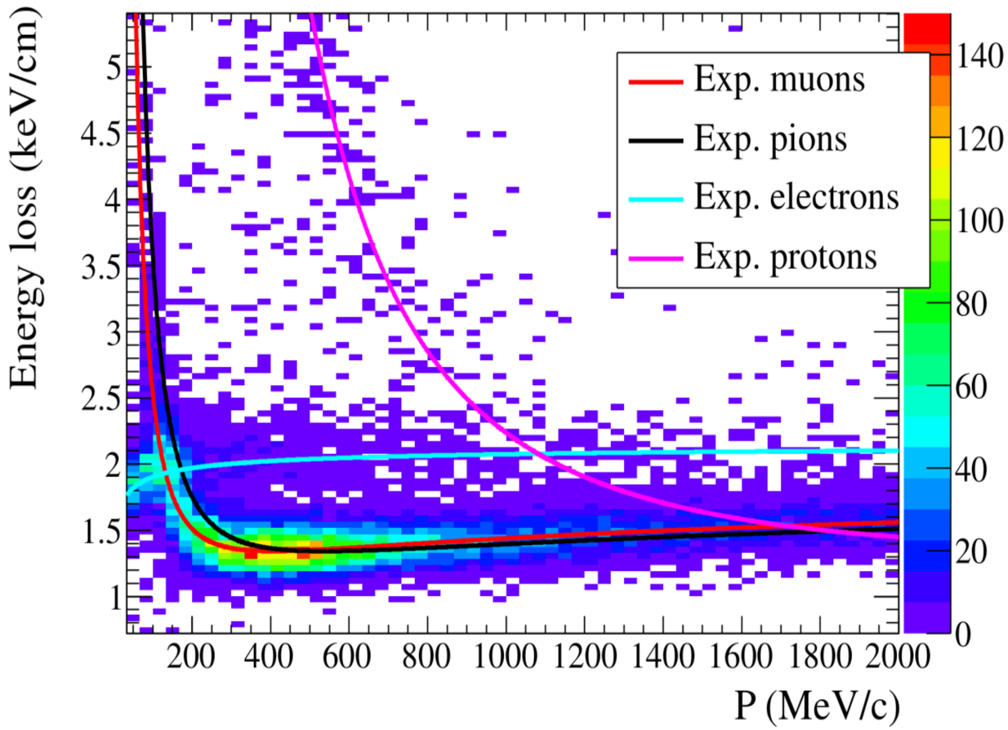


ND280 Measurements

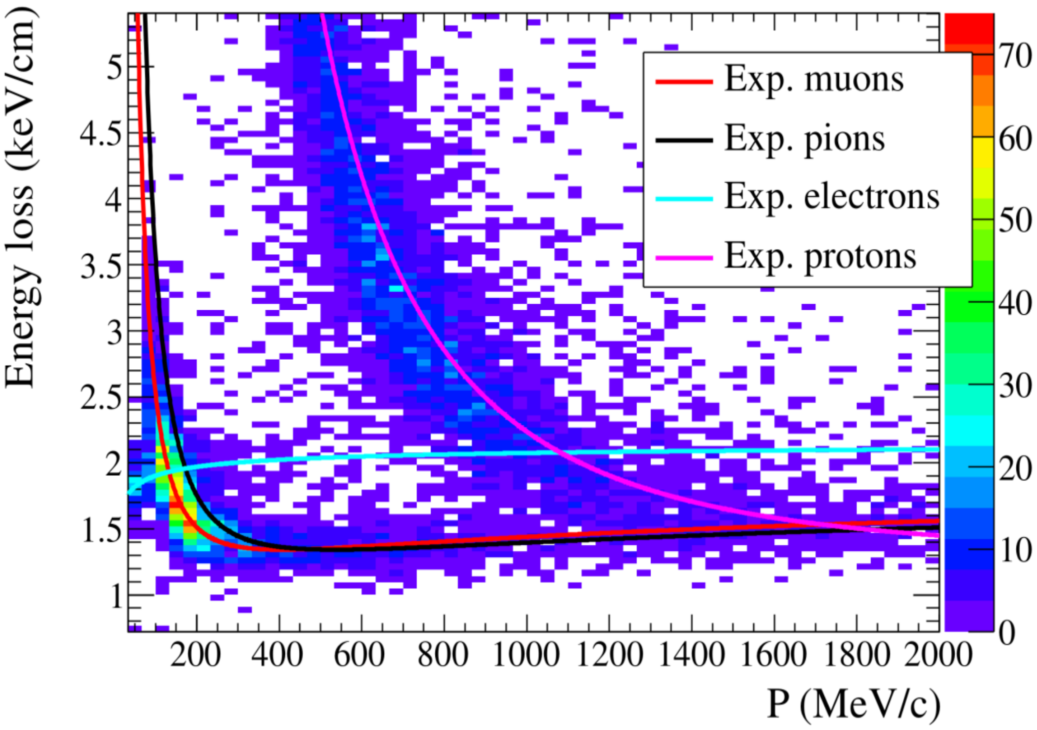
ND280 TPC Particle ID by dE/dx



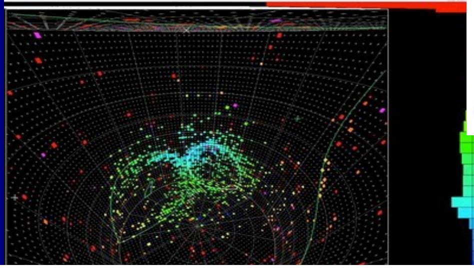
Negative tracks in the TPC.

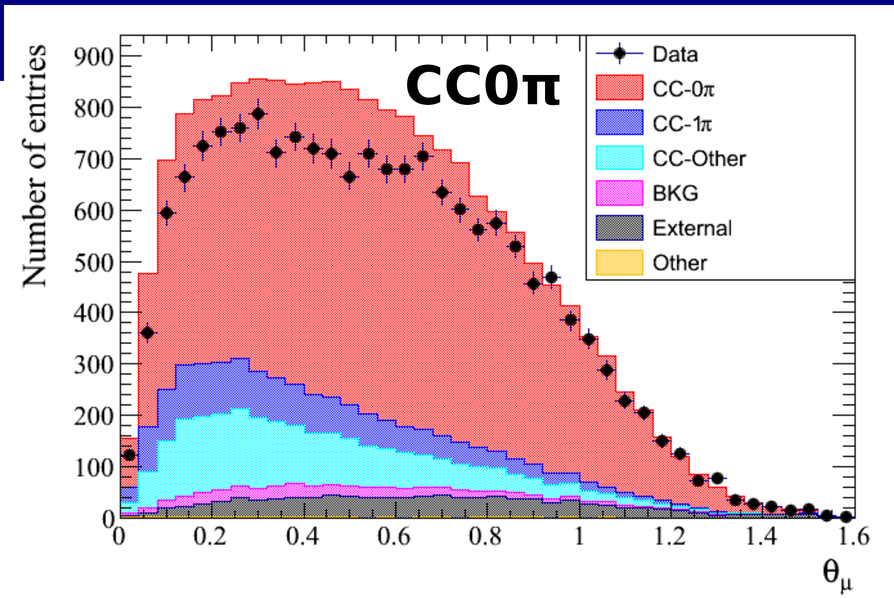


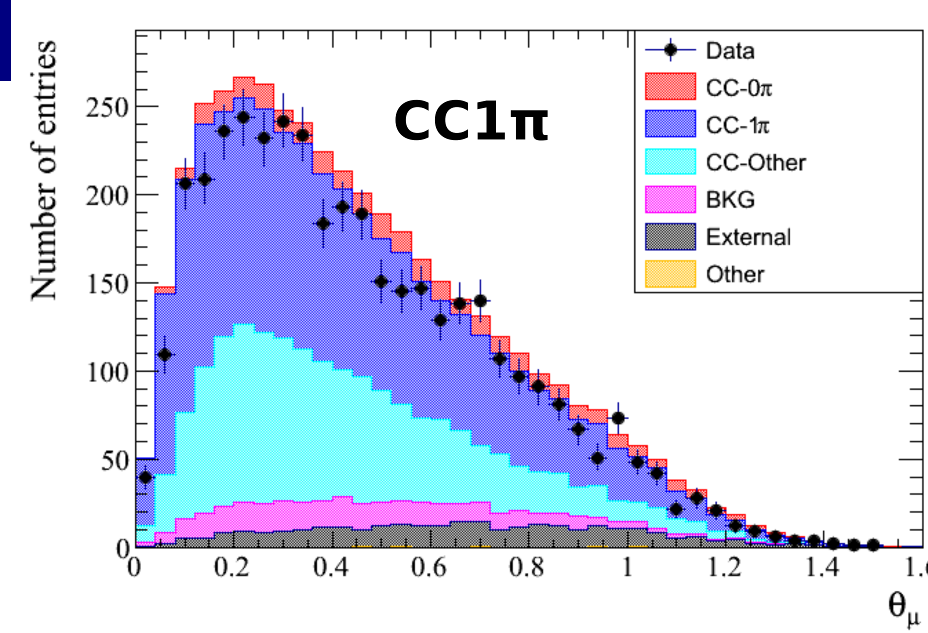
Positive tracks in the TPC.

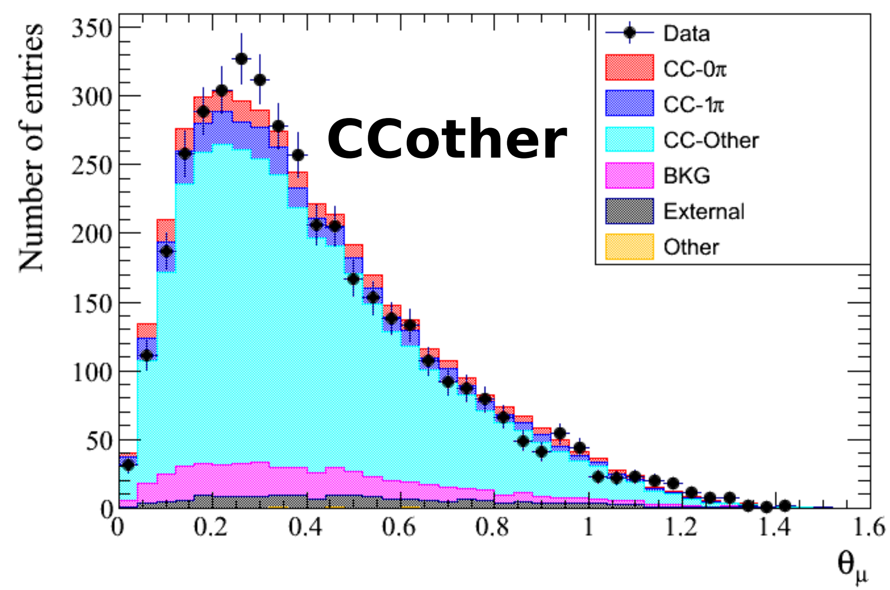


Muon Angle in ND280



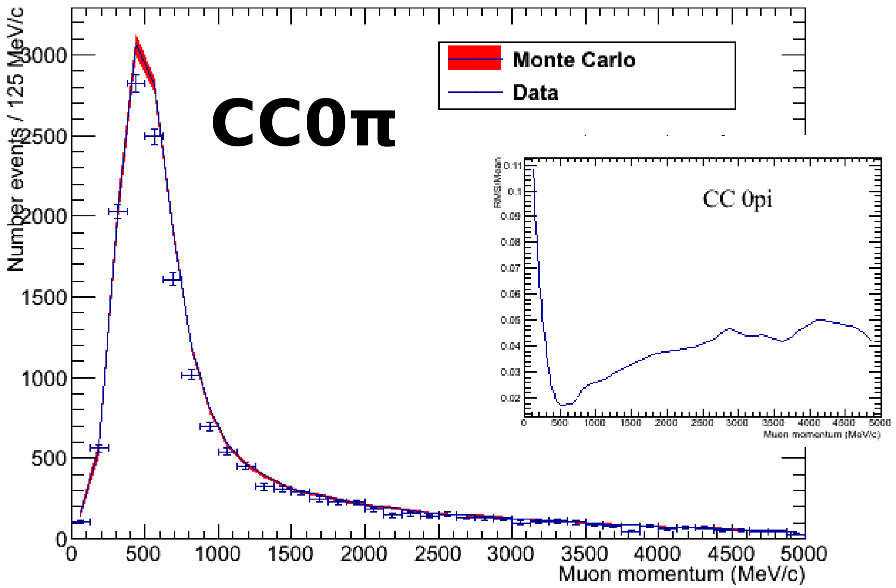


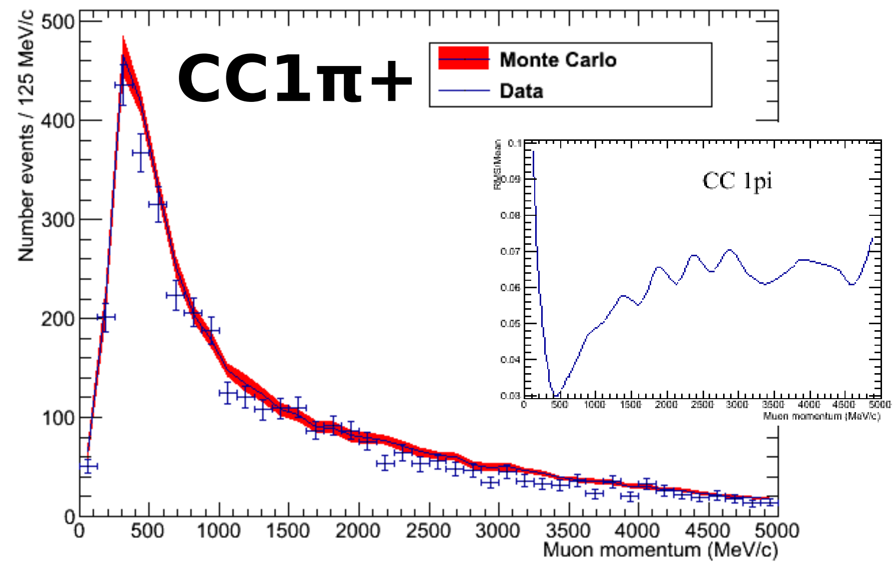


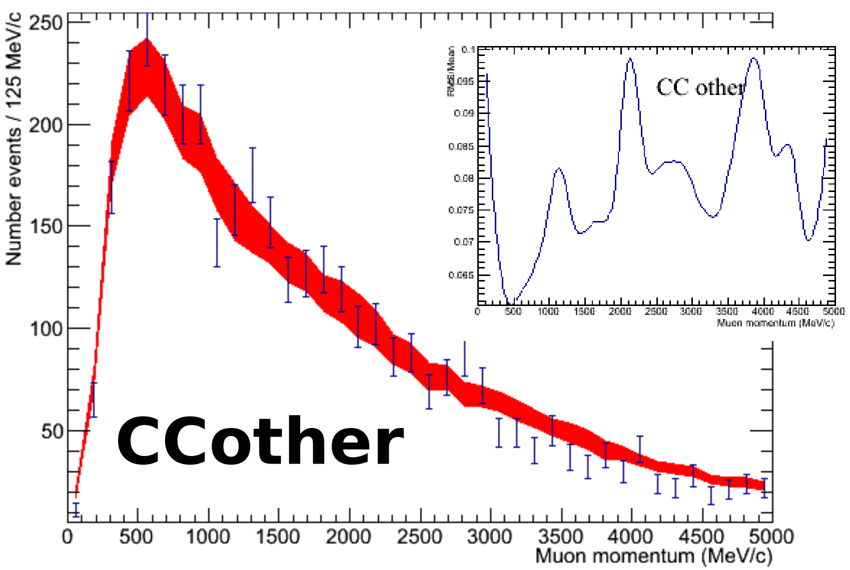


	CC0π purities	CC1π purities	CCother purities
CC0π	72.6%	6.4%	5.8%
CC1π	8.6%	49.4%	7.8%
CCother	11.4%	31%	73.8%
Bkg(NC+anti-nu)	2.3%	6.8%	8.7%
Out FGD1 FV	5.1%	6.5%	3.9%

ND280 Detector systematics



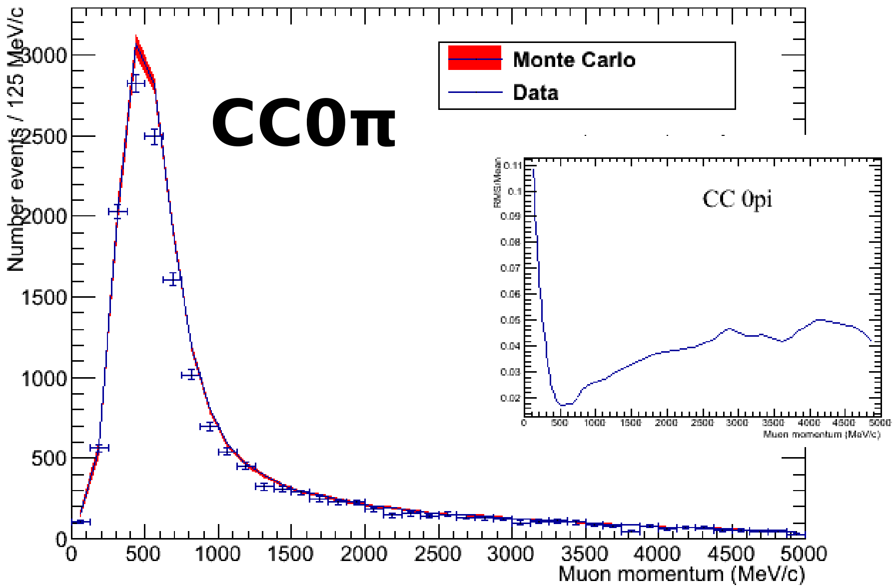


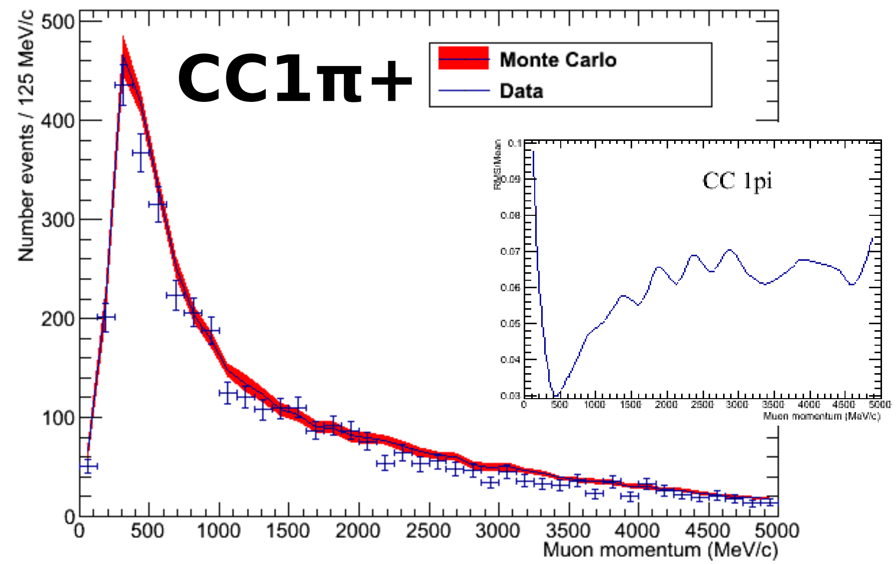


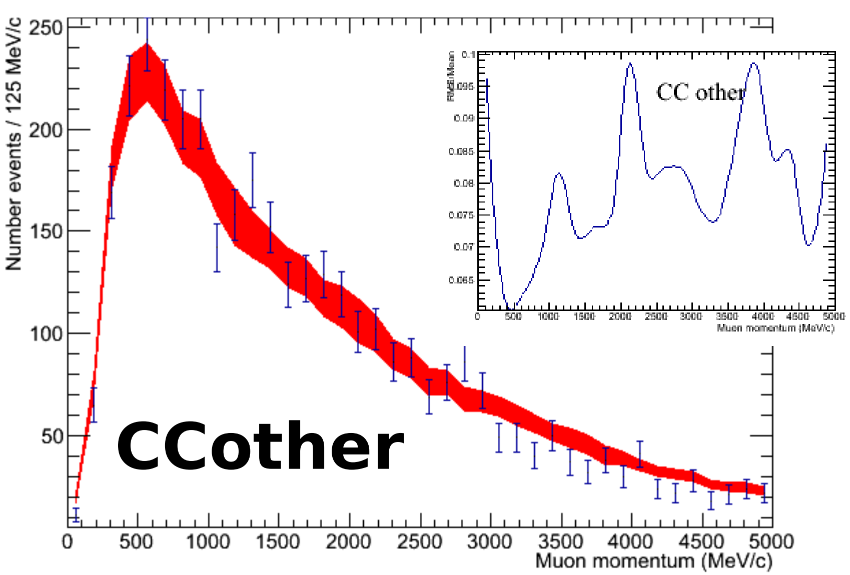
Largest relative error in all momentum bins in all categories

B Field distortion (0.3%)	TPC Tracking efficiency (0.6%)
TPC-FGD matching efficiency (1%)	**TPC Charge confusion (2.2%)**
TPC Momentum scale (2%)	**TPC Momentum resolution (5%)**
TPC Quality cut (0.7%)	Michel electron efficiency(0.7%)
FGD Mass(0.65%)	**Out of Fiducial Volume (10%)**
Pile-up (0.07%)	Sand muon (0.02%)
TPC PID (3.5%)	FGD PID (0.3%)
FGD tracking efficiency (1.4%)	**Pion secondary interaction (8%)**

ND280 Detector systematics







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TPC PID (3.5%)	FGD PID (0.3%)
FGD tracking efficiency (1.4%)	**Pion secondary interaction (8%)**

FLUX PREDICTION AND uncertainties

Fraction of the neutrino flux for each parent particle

Fraction for each flavors

	Flux Percentage of Each Flavors			
Parent	ν_μ	$\bar{\nu}_\mu$	ν_e	$\bar{\nu}_e$
Secondary				
$\pi^\pm$	60.0%	41.8%	31.9%	2.8%
$K^\pm$	4.0%	4.3%	26.9%	11.3%
K_L^0	0.1%	0.9%	7.6%	49.0%
Tertiary				
$\pi^\pm$	34.4%	50.0%	20.4%	6.6%
$K^\pm$	1.4%	2.6%	10.0%	8.8%
K_L^0	0.0%	0.4%	3.2%	21.3%

Total fraction for all flavors

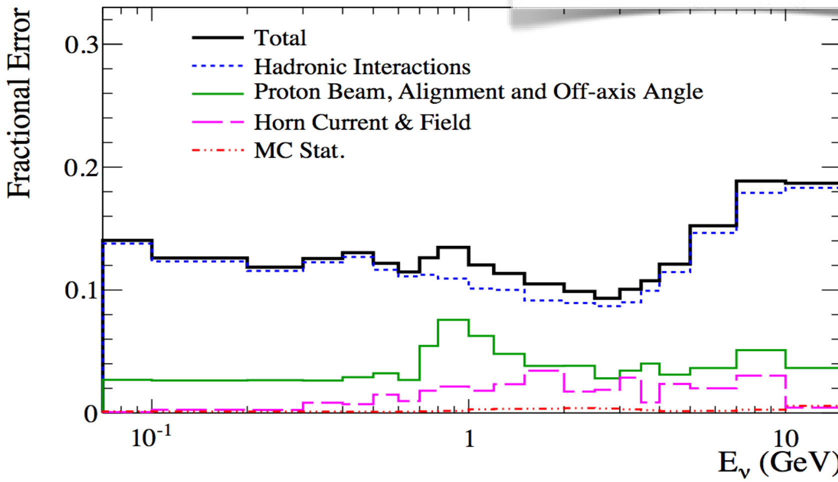
	Flux Percentage of All Flavors			
Parent	ν_μ	$\bar{\nu}_\mu$	ν_e	$\bar{\nu}_e$
$\pi^\pm$	87.5%	5.5%	0.6%	0.0%
$K^\pm$	5.0%	0.5%	0.4%	0.0%
K_L^0	0.1%	0.2%	0.1%	0.1%

Flux uncertainty as a function of energy

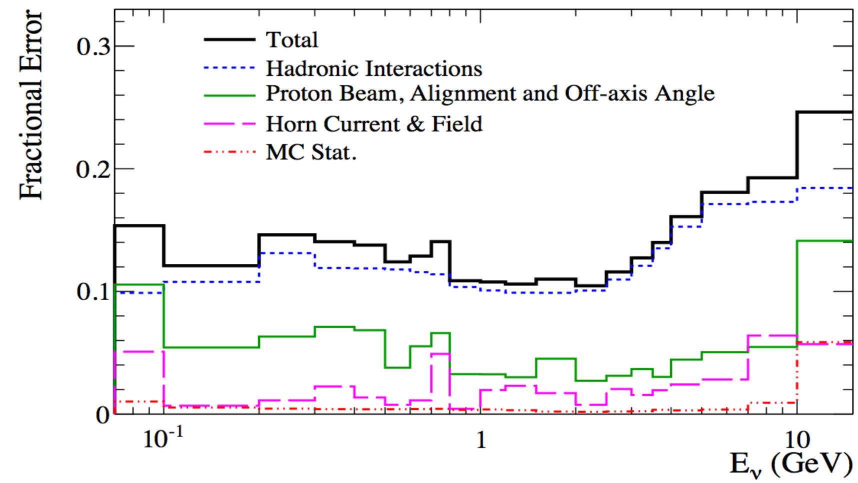
uncertainties are evaluated based on NA61 measurements and T2K beam monitor measurements

SK νμ flux

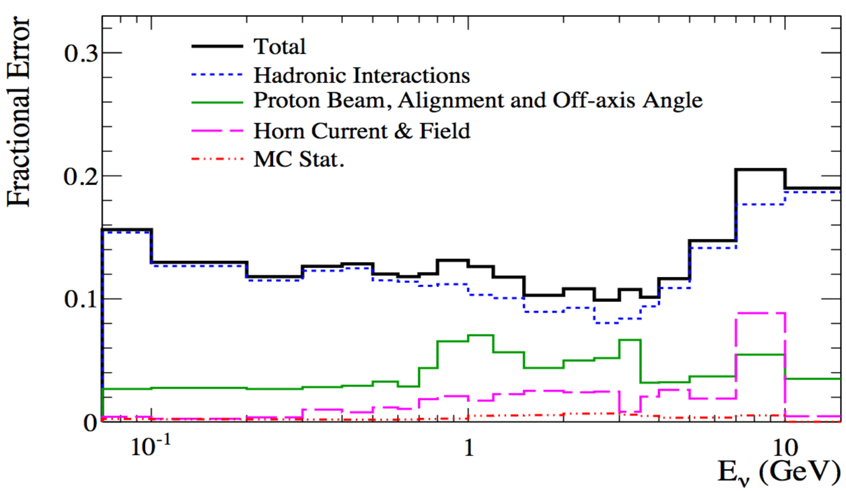
10~15% error



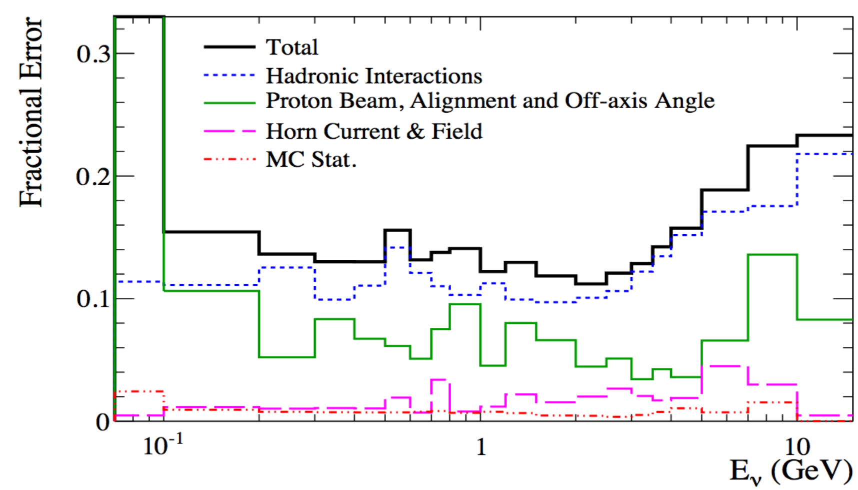
SK νe flux



ND280 νμ flux



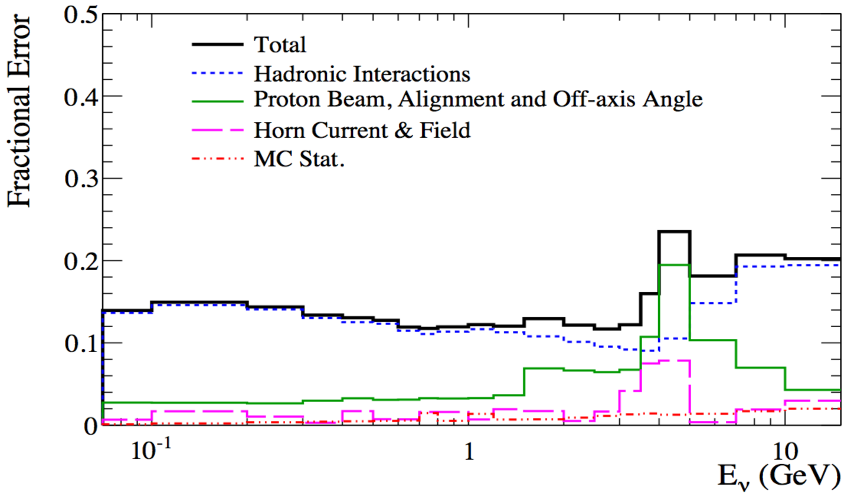
ND280 νe flux



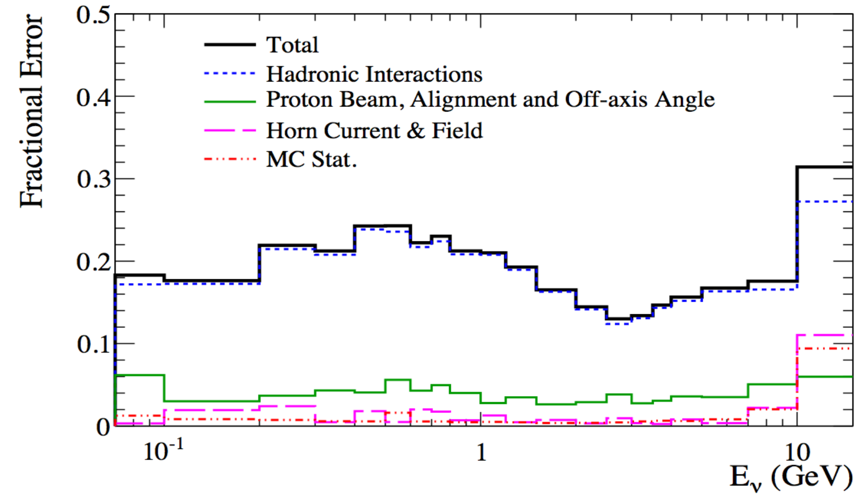
Flux uncertainty as a function of energy

uncertainties are evaluated based on NA61 measurements and T2K beam monitor measurements

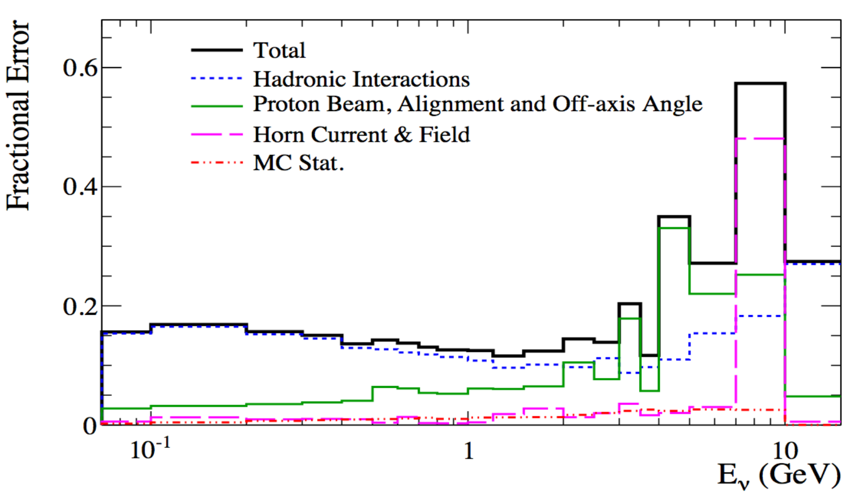
SK νμ flux



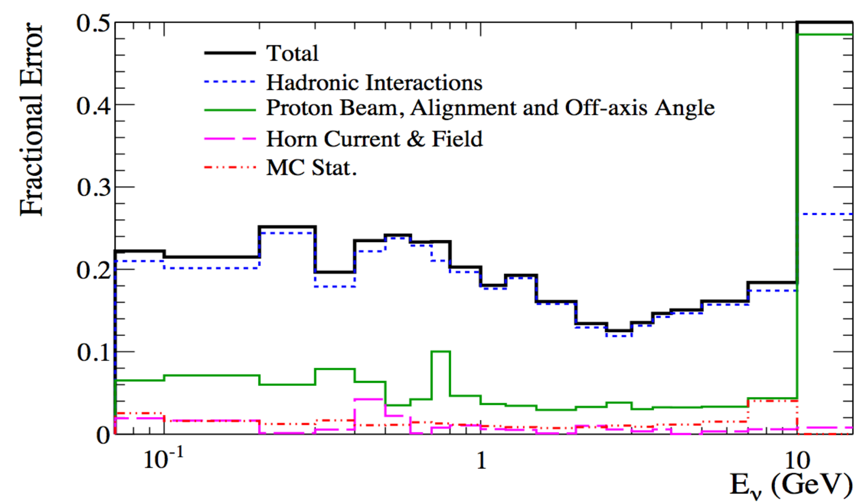
SK νe flux



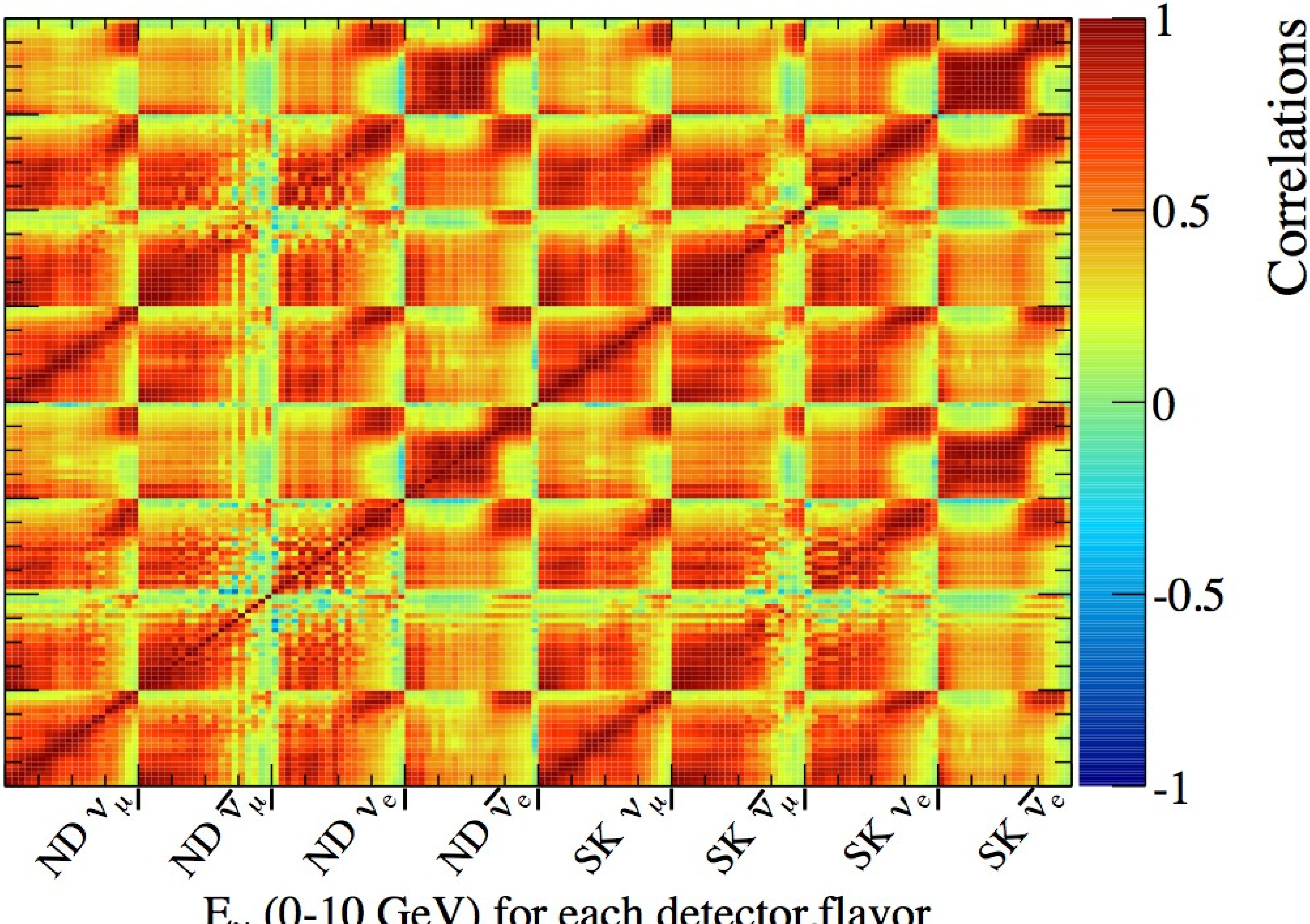
ND280 νμ flux

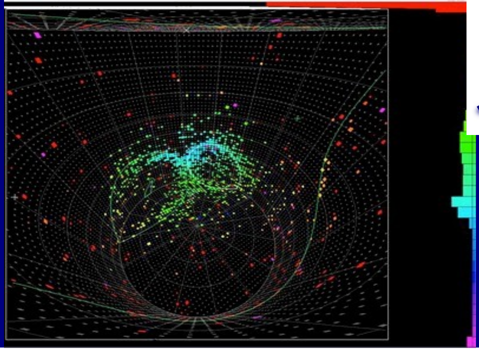


ND280 νe flux



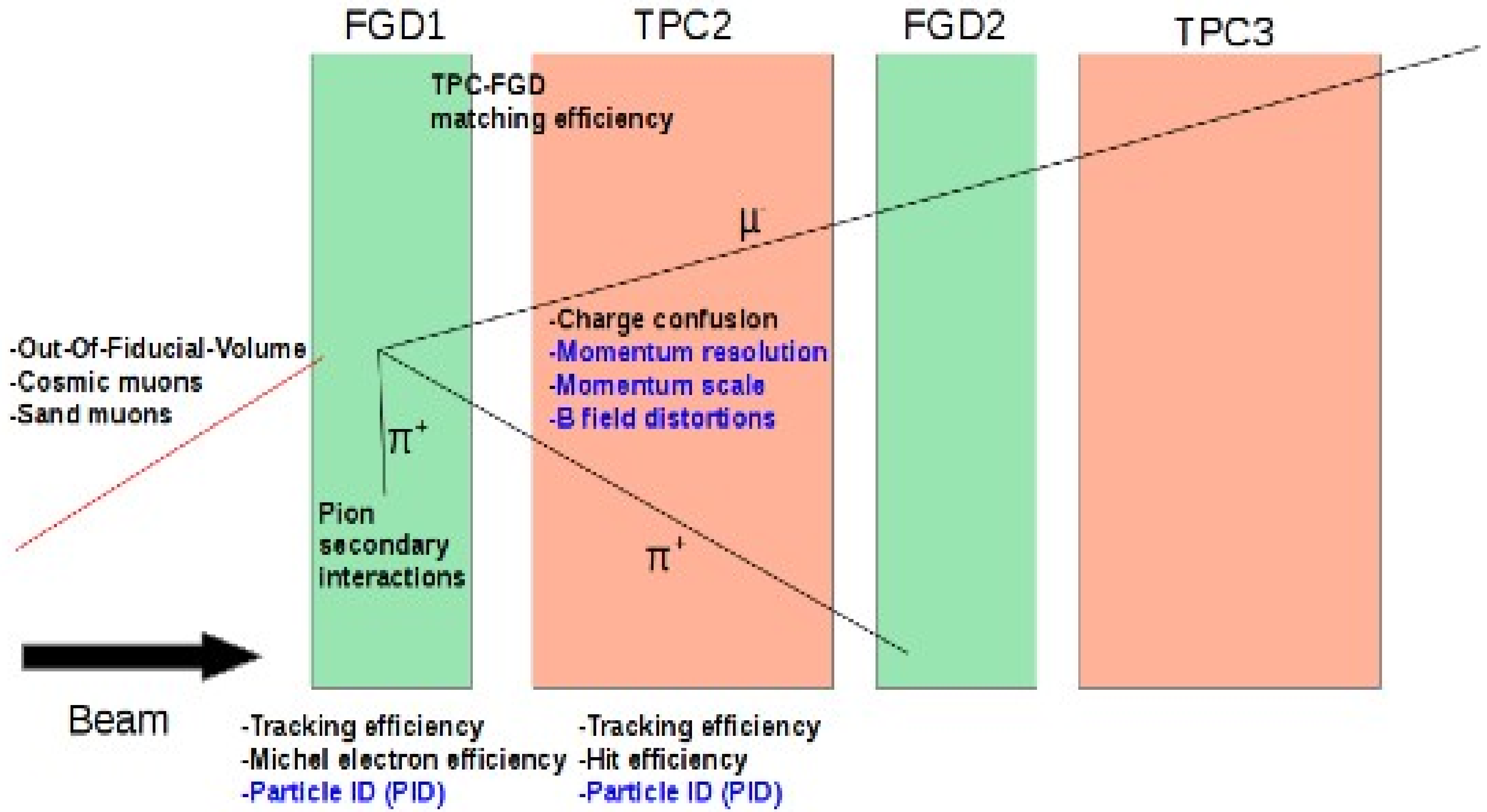
energy dependent errors w/ full correlations among ν types and between detectors(ND280, SK) are taken into account



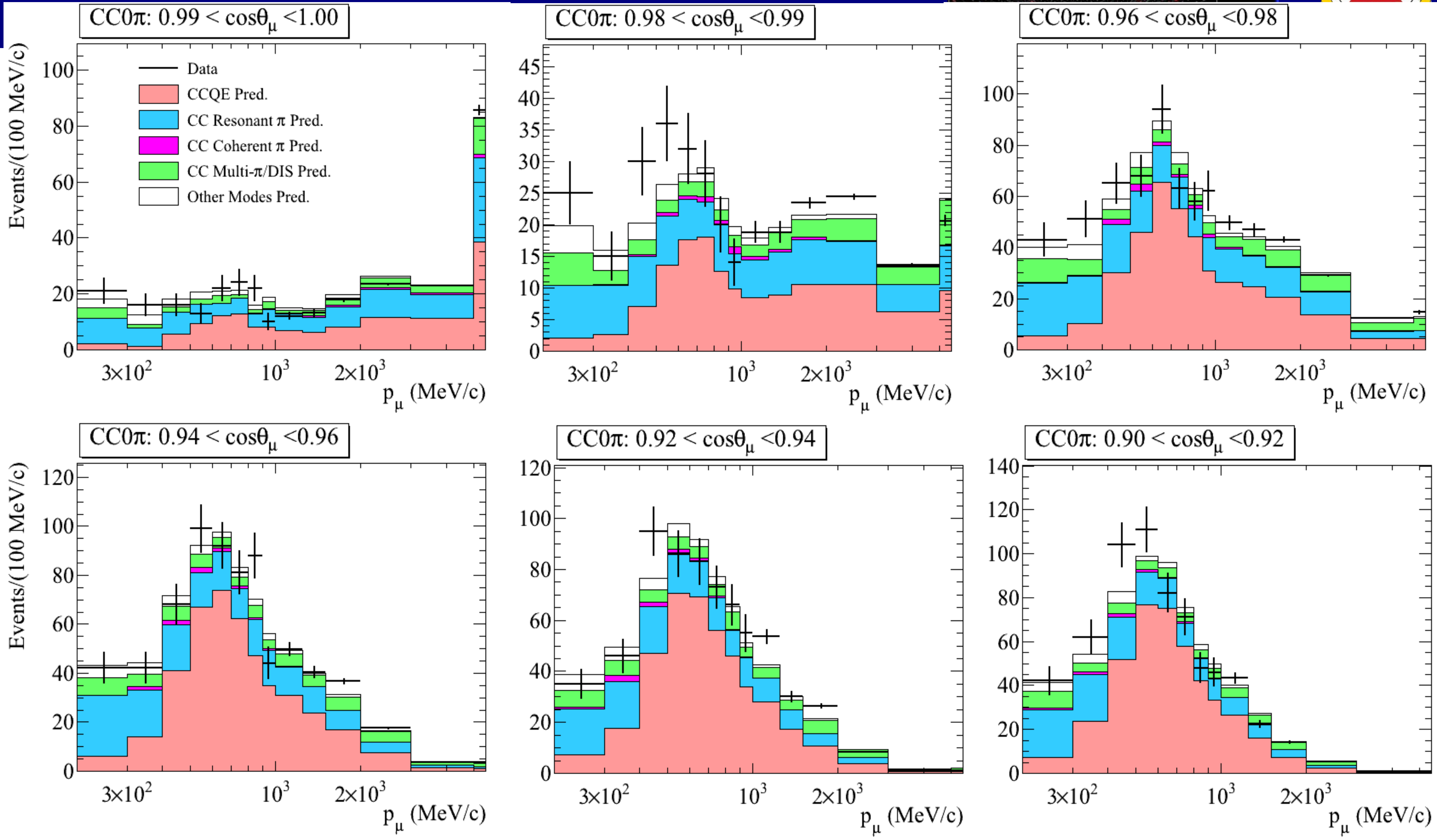


ND280 Constraint Fits

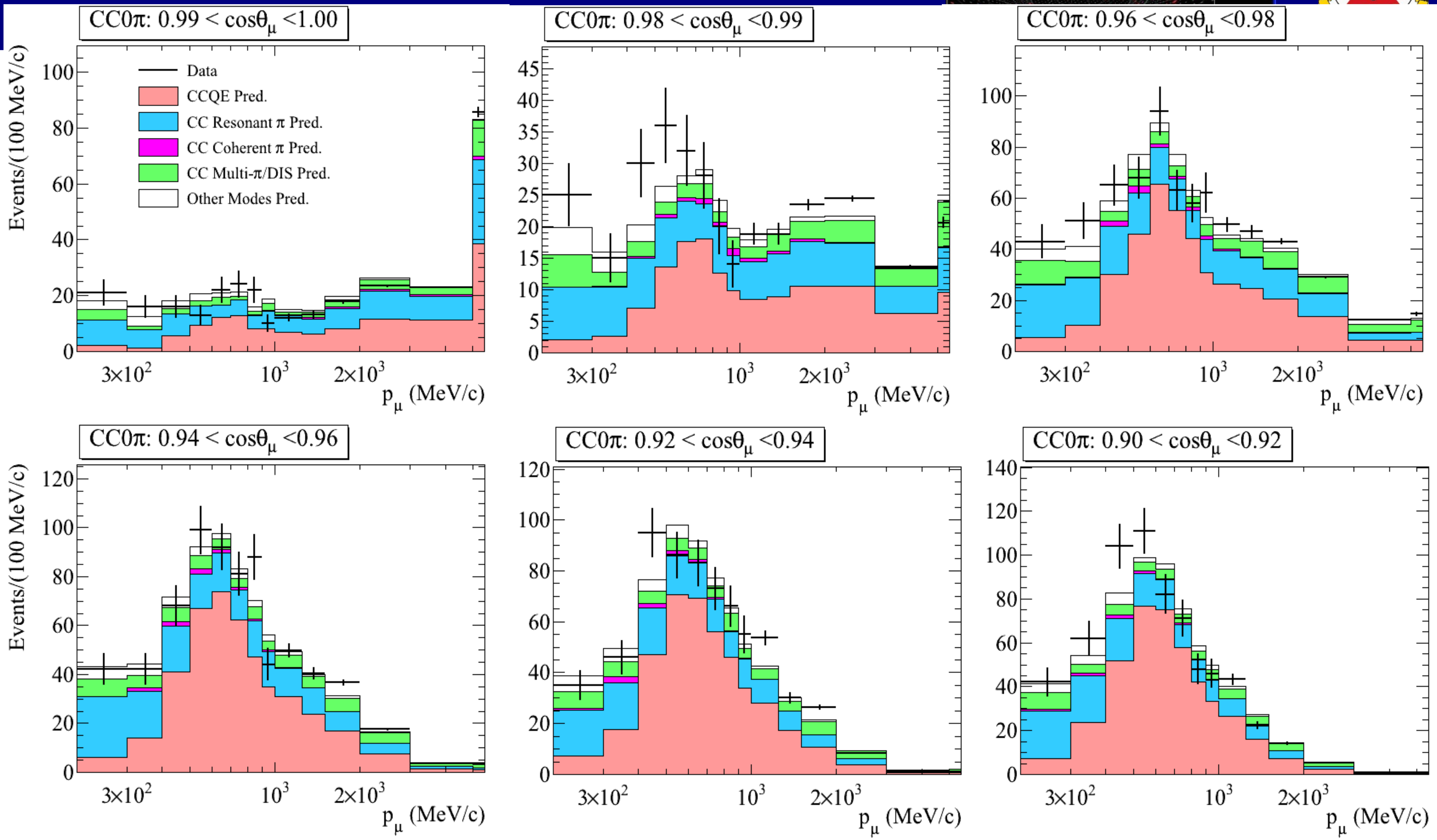
ND280 Systematic Errors



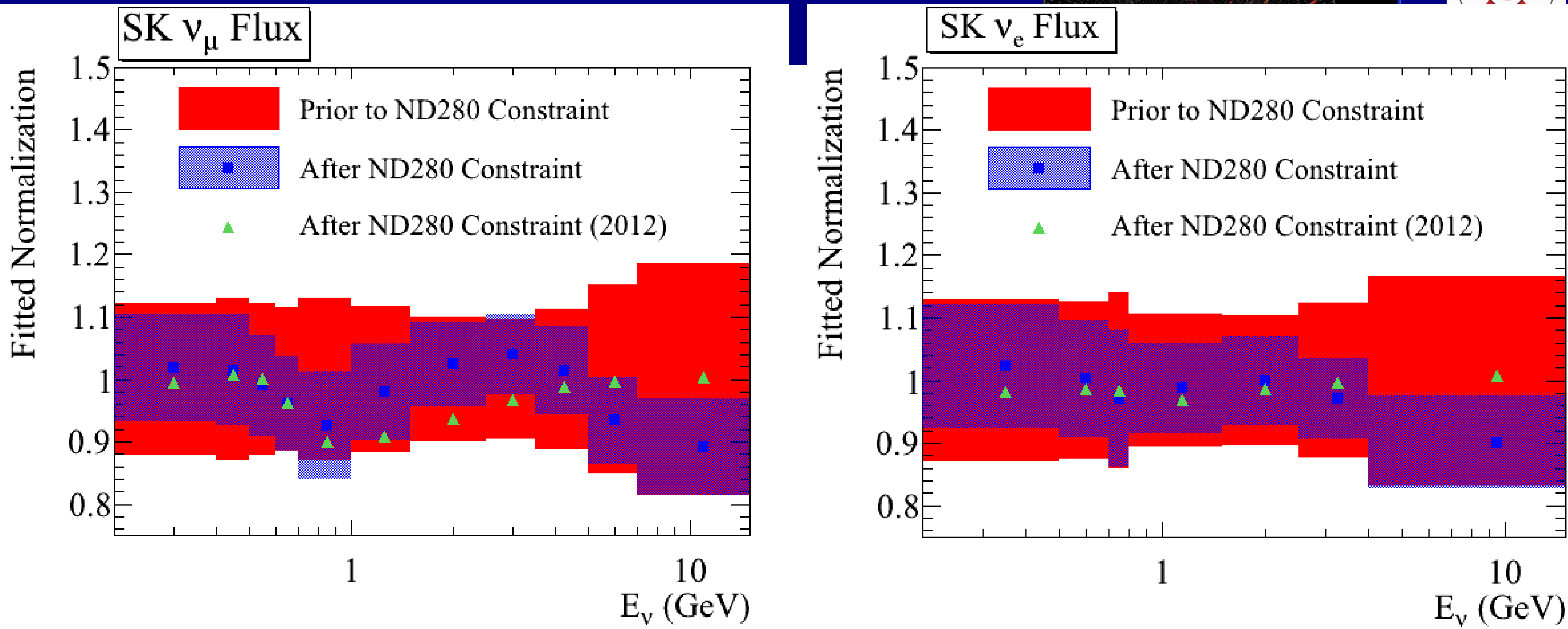
ND CC0π Prediction and Data after ND280 Constraint



ND CC0π Prediction and Data after ND280 Constraint



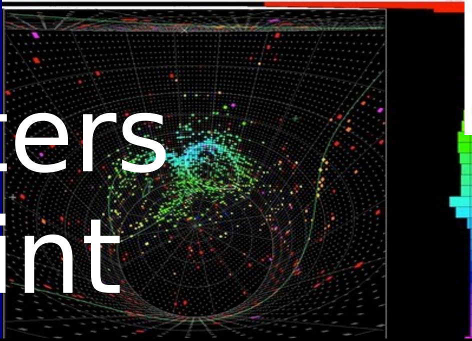
Flux after ND280 Constraint



Far detector νμ and νe flux predictions are constrained by the fit, as illustrated by the central values and error bands for normalization vs. neutrino energy, before and after ND280 constraint.

(Central values are changed from 2012 results: due to finer bins and new ND280 selection)

Cross-Section Parameters after ND280 Constraint

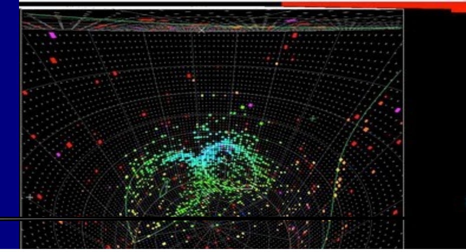


Parameter	Prior to ND280 Constraint	After ND280 Constraint (Runs 1-4)	After ND280 Constraint (2012 analysis, Runs 1-3)
MAQE (GeV)	1.21 ± 0.45	1.223 ± 0.072	1.269 ± 0.194
MARES (GeV)	1.41 ± 0.22	0.963 ± 0.063	1.223 ± 0.127
CCQE Norm.*	1.00 ± 0.11	0.961 ± 0.076	0.951 ± 0.086
CC1π Norm.**	1.15 ± 0.32	1.22 ± 0.16	1.37 ± 0.20
NC1π0 Norm.	0.96 ± 0.33	1.10 ± 0.25	1.15 ± 0.27

*For Eν<1.5 GeV **For Eν<2.5 GeV

Significant changes to MARES and CC1π normalization parameters and reduction in uncertainties since 2012 analysis due to finer bins and new selection that explicitly identified CC1π+ events.

ND280 Fit Δχ2



$$\Delta\chi^2 = 2\sum_{i}^{p,\cos\theta\ bins} N_i^{pred}(\vec{b},\vec{x},\vec{d}) - N_i^{data} + N_i^{data}\ln[N_i^{data}/N_i^{pred}(\vec{b},\vec{x},\vec{d})]$$

$$+\sum_{i}^{E_\nu\ bins}\sum_{j}^{E_\nu\ bins}(1-b_i)(V_b^{-1})_{i,j}(1-b_j) + \sum_{i}^{xsec\ pars}\sum_{j}^{xsec\ pars}(x_i^{nom}-x_i)(V_x^{-1})_{i,j}(x_j^{nom}-x_j)$$

$$+\sum_{i}^{p,\cos\theta\ bins}\sum_{j}^{p,\cos\theta\ bins}(d_i^{nom}-d_i)(V_d^{-1})_{i,j}(d_j^{nom}-d_j)$$

b = flux nuisance parameters
x = cross section nuisance parameters
d = detector/reconstruction model nuisance parameters
Vb,Vx,Vd = covariance matrices (pre-fit uncertainties)

$$N_i^{pred}(\vec{b},\vec{x},\vec{d}) = d_i \sum_{j=1}^{MC\ Events} b_j x_j^{norm} w_j^x(\vec{x})$$

Pre-calculated weight function for cros section parameters with non-linear response

Results from Fit to ND280 Data

Selection	Number of Events (Data)	Number of Events (MC before ND280 constraint)	Number of Events (MC after ND280 constraint)
CC0π	16912	20016	16803
CC1π	3936	5059	3970
CC Other	4062	4602	4006
CC Inclusive	24910	29678	24779

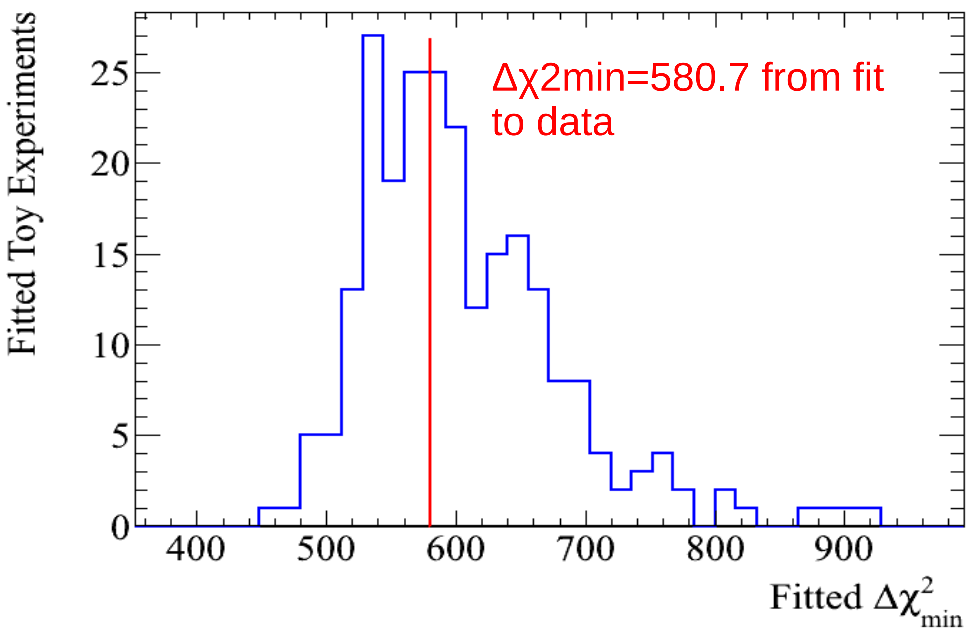
Test the data and constrained MC agreement with toy experiments:

Generated variations of models within prior uncertainties

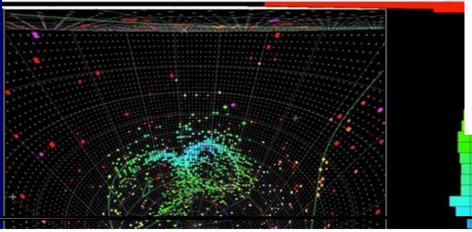
Fit toy data in same manner as data

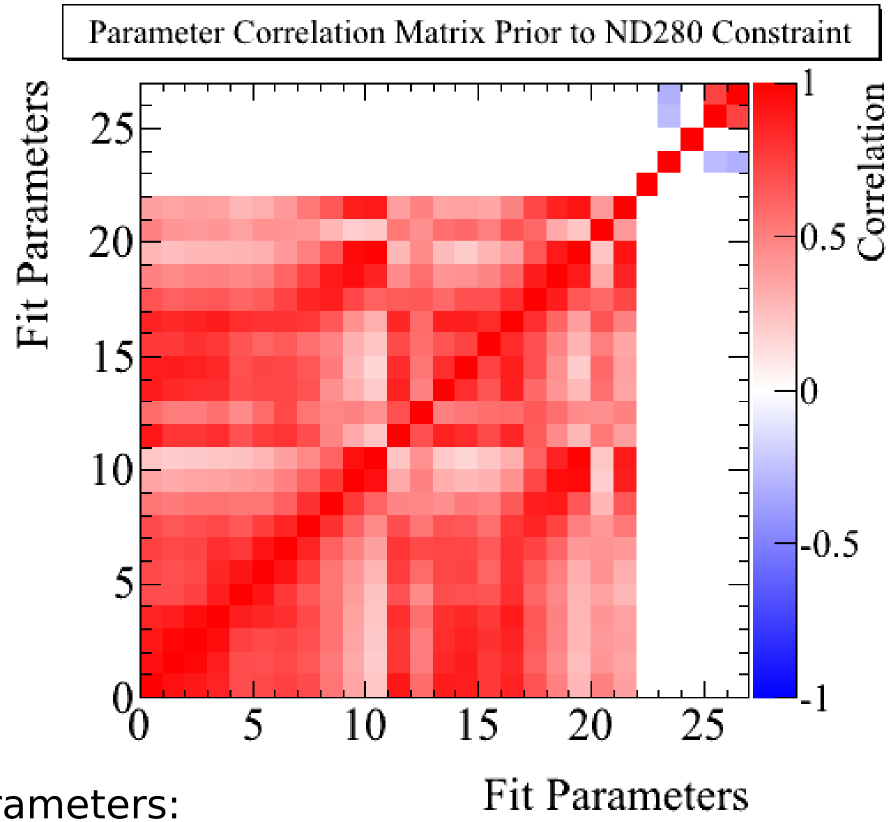
Record Δχ2 at minimum for each toy fit

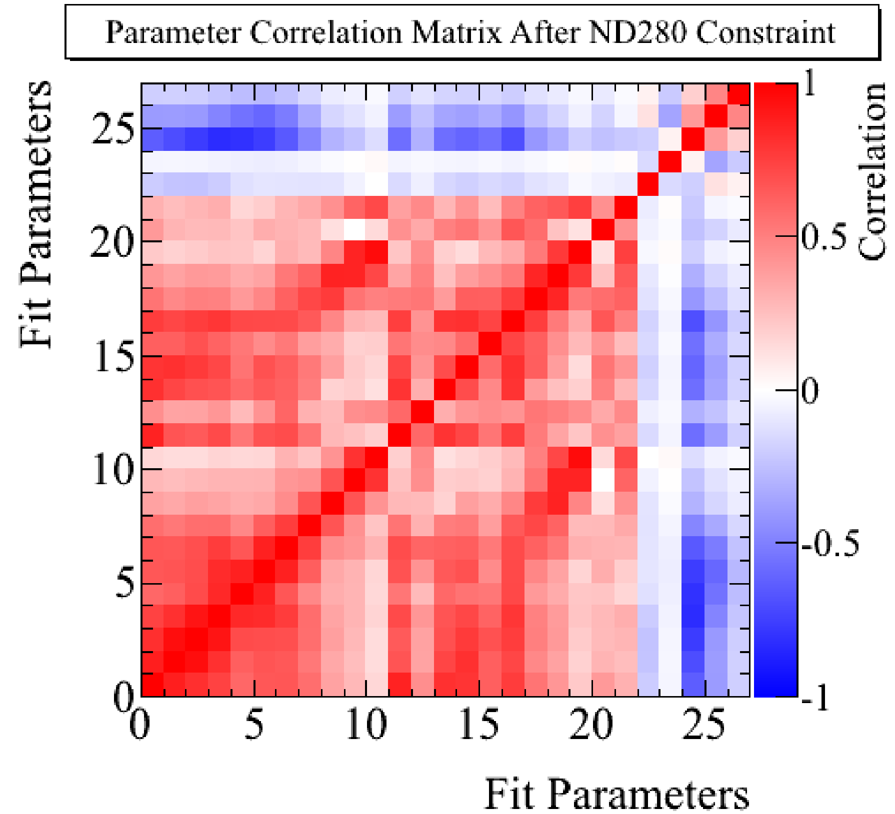
Δχ2min=580.7 for data has p-value of 0.57



Parameter Correlations







Parameters:

0-10: SK νμ flux

11-12: SK νμ flux

13-19: SK νe flux

20-21: SK νe flux

22: MAQE

23: MARES

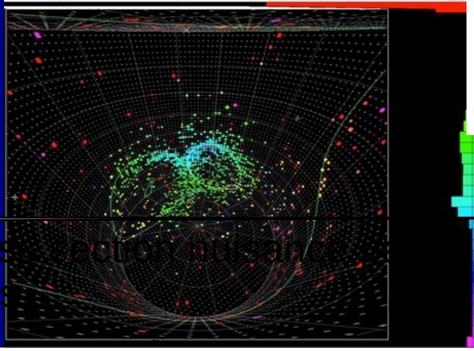
24: CCQE Norm.

25: CC1π Norm.

26: NC1π0 Norm.

The constraint from the measured event rates causes anti-correlations between flux and cross section nuisance parameters

SK Uncertainty Reduction



Reduction of uncertainty on the SK prediction from constrained flux and cross section nuisance parameters is due to increased statistics and improved SK and ND280 analysis techniques

ND280 Analysis	ND280 Data	SK Selection	$\sin^2 2\theta_{13}=0.1$	$\sin^2 2\theta_{13}=0.0$
No Constraint	--	Old	22.6%	18.3%
No Constraint	--	New	26.9%	22.2%
2012 method*	Runs 1-2	Old	5.7%	8.7%
2012 method**	Runs 1-3	Old	5.0%	8.5%
2012 method	Runs 1-3	New	4.9%	6.5%
2012 method***	Runs 1-3	New	4.7%	6.1%
2013 method	Runs 1-3	New	3.5%	5.2%
2013 method	Runs 1-4	New	3.0%	4.9%

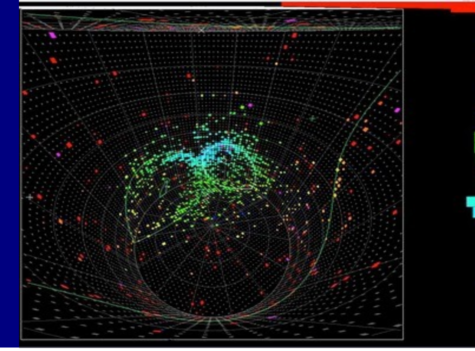
Factor 2.4 more ND28 POT

Improved SK π0 rejection

New ND280 reconstruction, selection, binning

Factor 2.2 more ND280 POT

*Results presented at Neutrino 2012 conference
**Published results, arXiv:1304.0841v2
***Update to NEUT tuning with MiniBooNE data



Super-K Detector Systematic Uncertainties

SK errors with atmospheric-νe

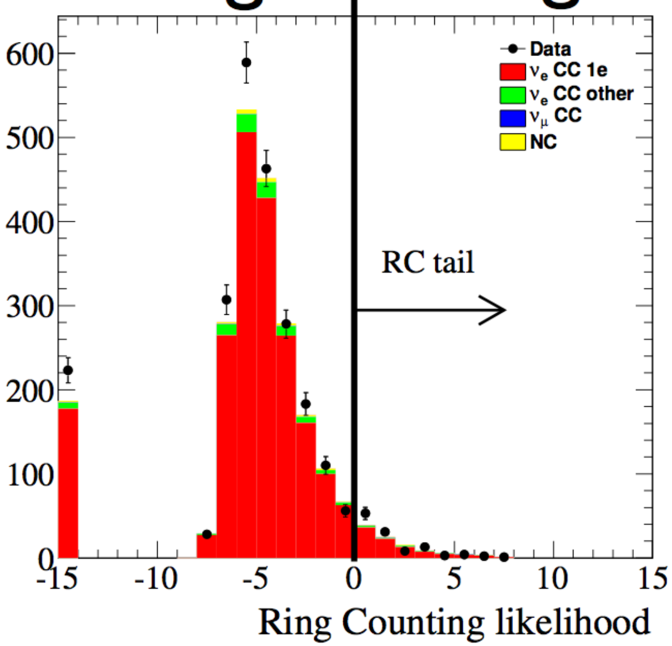
- Evaluate the errors on 'νe selection efficiencies' using SK atmospheric neutrino samples
  - Errors on ring counting (RC), particle identification (PID), and π0 rejection
  - (cf. νe candidates: 1-ring & e-like & no π0-like)

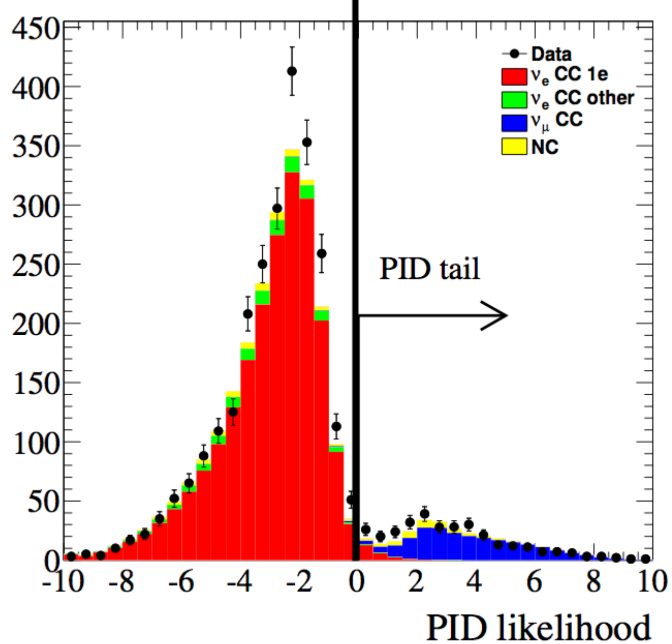
- Use SK atmospheric neutrino data of 1417.4 days live-time for the 2013 analysis

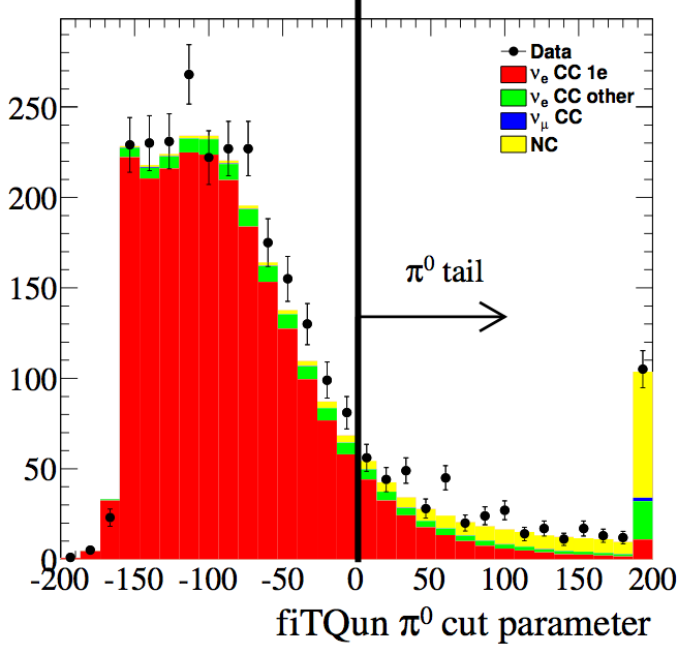
Control Samples

- νe candidate sample ("core" sample) + rejected samples (three "tail" samples)
  - Selections: ring counting, PID, and π0 rejection
  - (cf. νe candidates: 1-ring & e-like & none π0-like)

Ring Counting	PID	π0 rejection
Single ring | Multi-ring	e-like | μ-like	none π0-like | π0-like

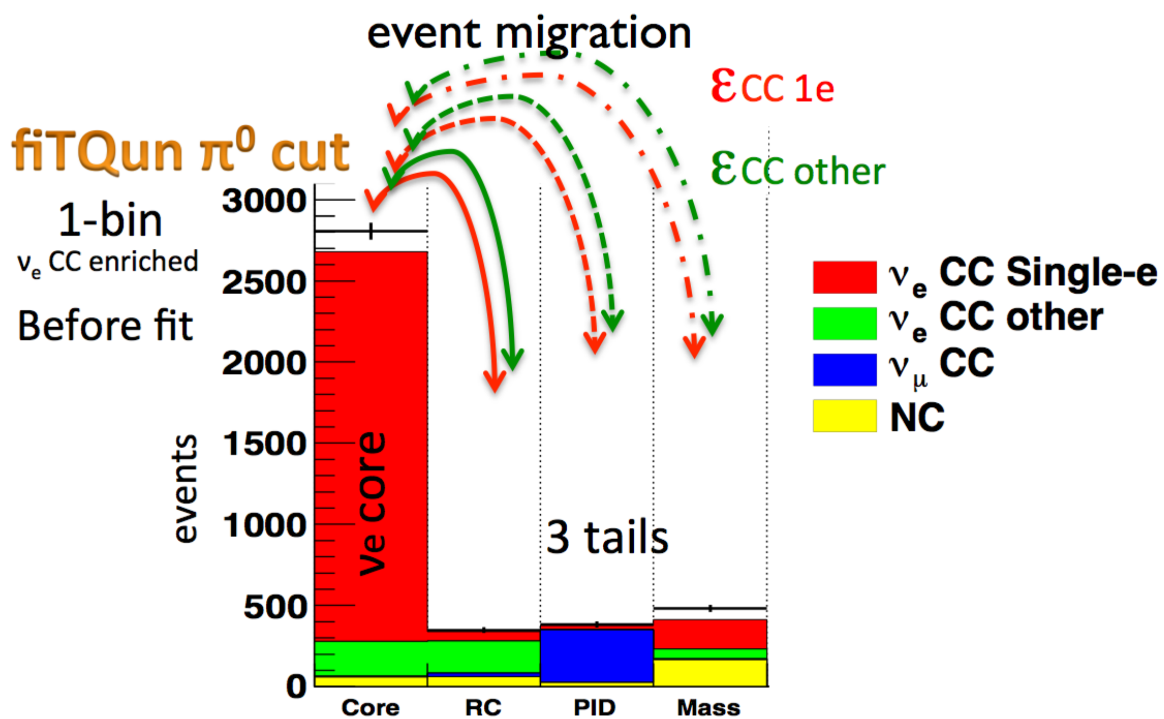






Atmospheric ν fit

- Evaluate errors on 'νe selection efficiencies' by fit the MC predictions to data by introducing the efficiency parameters ε, that describes event migration between 'core' and 'tail' samples

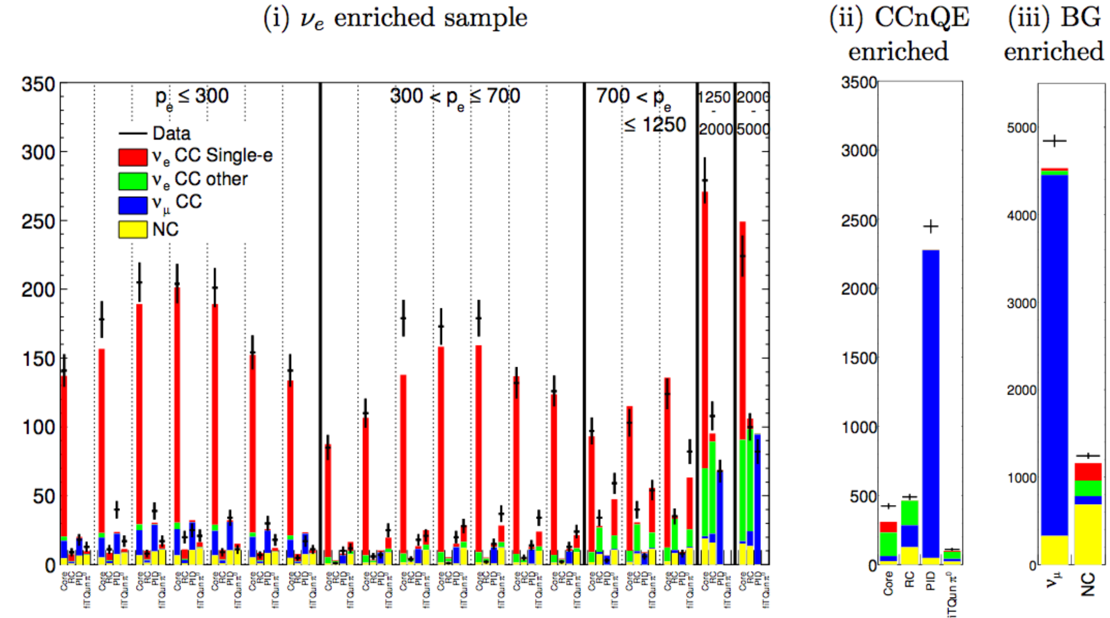


- Evaluate the errors in bins of momentum (p) and scattered angle (θ)
  - p bins: 100, 300, 700, 1250, 2000, 5000 MeV/c
  - θ bins: 0, 40, 60, 80, 100, 120, 140, 180 deg.

atm-ν fit results

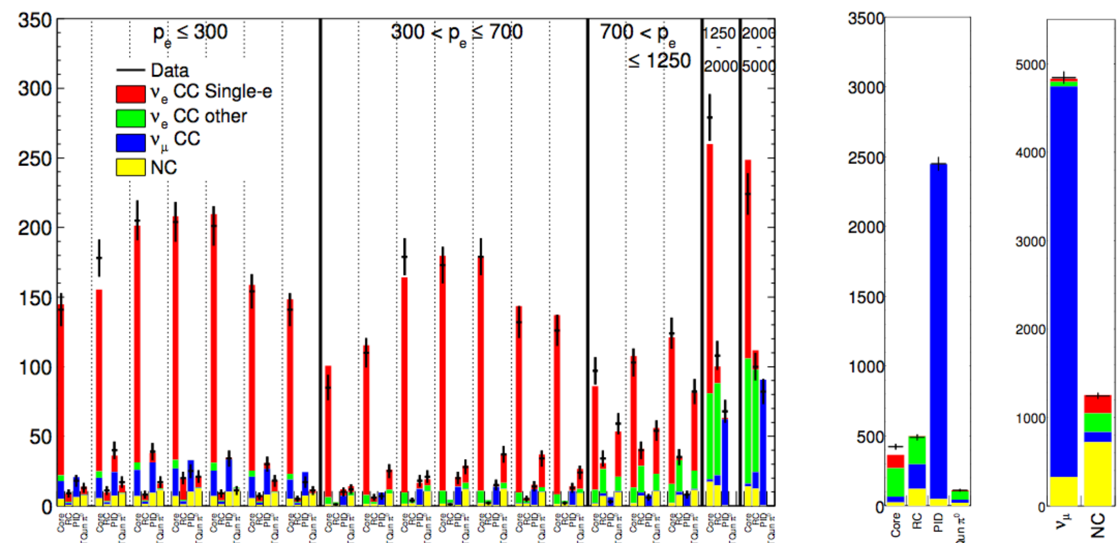
Number of events in p-θ bins and control samples.

Before fit



(a) Before atm-ν fit (Original MC) ($\chi^2 = 336.8$)

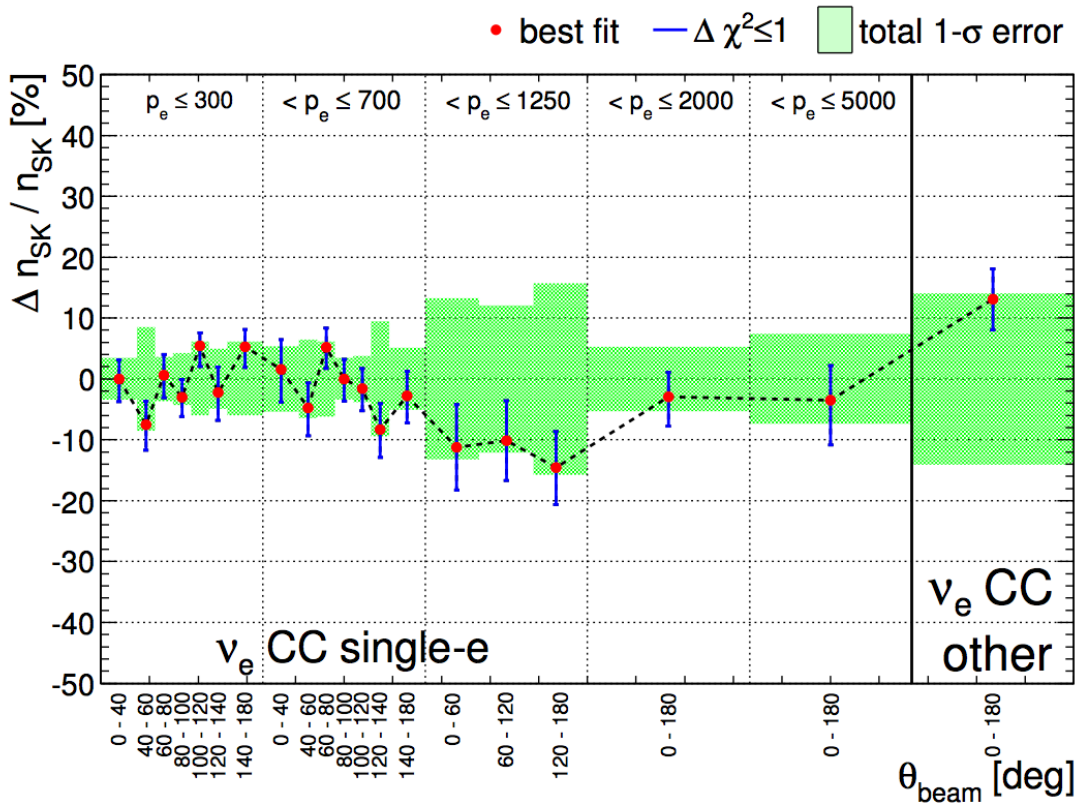
Best fit



(b) Best fit (Minimized all parameters) ($\chi^2 = 165.4$) / ($d.o.f. = 186\text{bins} - 58 = 128$)

SK error w/ atm-ν fit

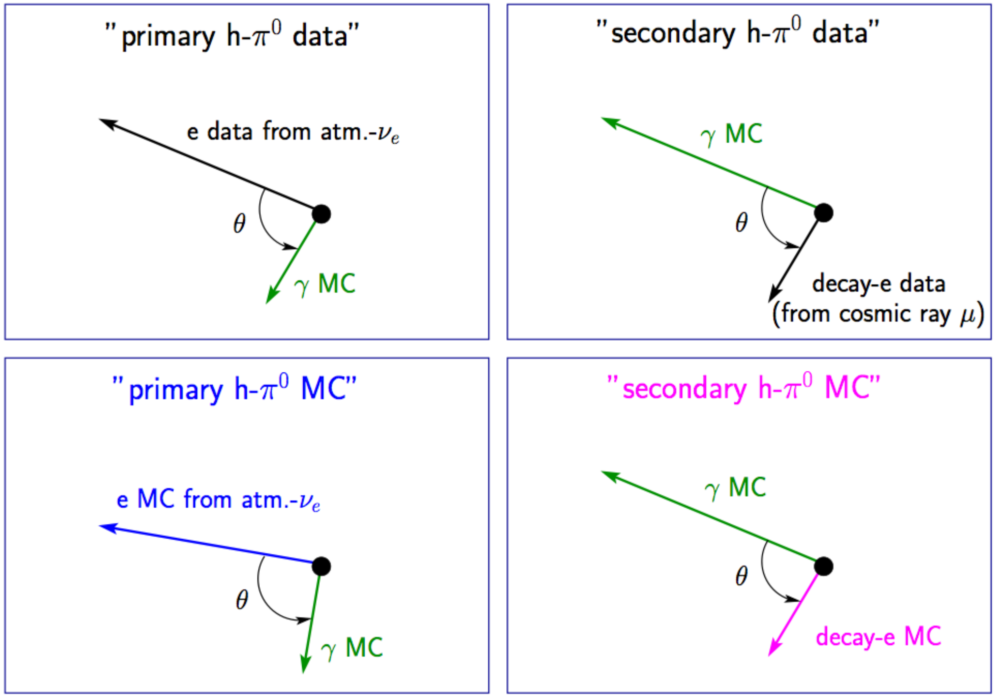
- Errors on number of νe candidates (n_{SK}) in 19 p-θ bins for 'νe CC single-electron' events and 1 bin for 'νe CC other' events
  - Correlated error (red point): difference from the 'best fit'
  - Uncorrelated error (blue bar): fit error (stat. error)



Monday, July 15, 13

"Hybrid-π0" samples

- "Hybrid-π0" samples
  - Electron track from atm-ν data is combined with γ from MC following π0 decay kinematics



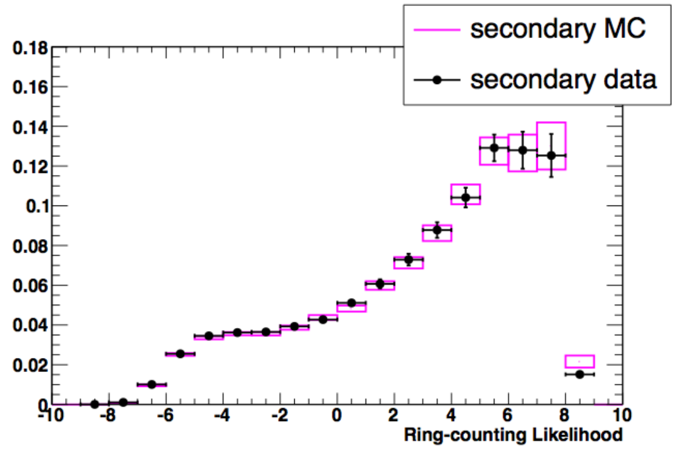
- Control samples:
  - Primary: electron from atm-ν is used for the higher energy "γ", and the lower energy γ from MC
  - Secondary: electron of atm-νe (and decay-e from cosmic-ray μ) is the lower energy "γ", and higher energy γ from MC

Control samples

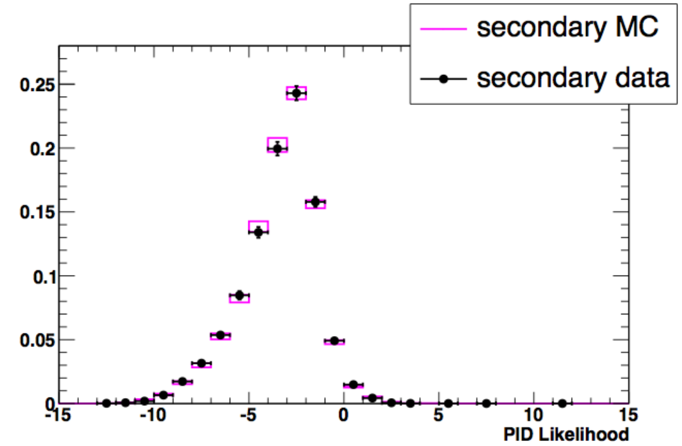
- Three type of control samples:
  - "NC hybrid-π0" sample
  - "NC hybrid-π0 + other" sample
  - "νμ CC hybrid-π0 + other" sample
  - where "other" includes charged pions, and protons (and their combinations)
- All samples have 'primary' and 'secondary' samples
- The errors are evaluated in p-θ bins (the same definition as atm-ν fit)

Basic distributions

Ring Counting

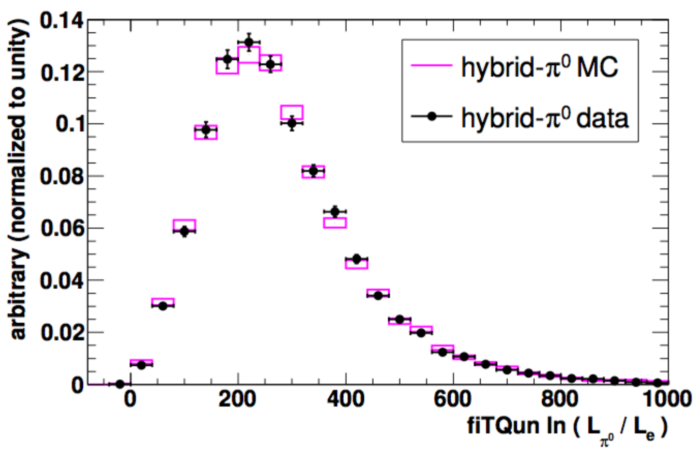


PID

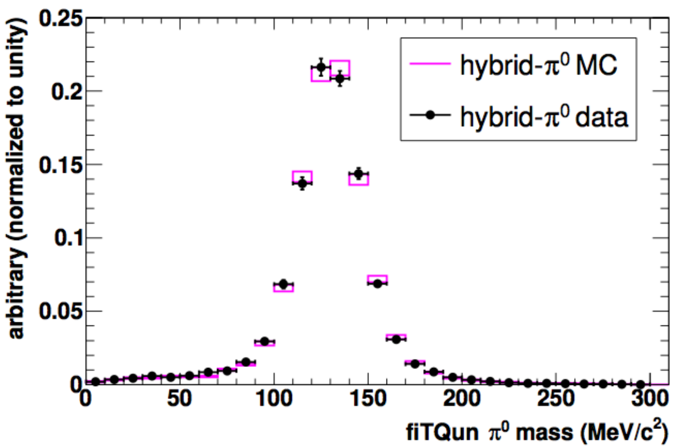


π0 rejection

π0/e likelihood ratio



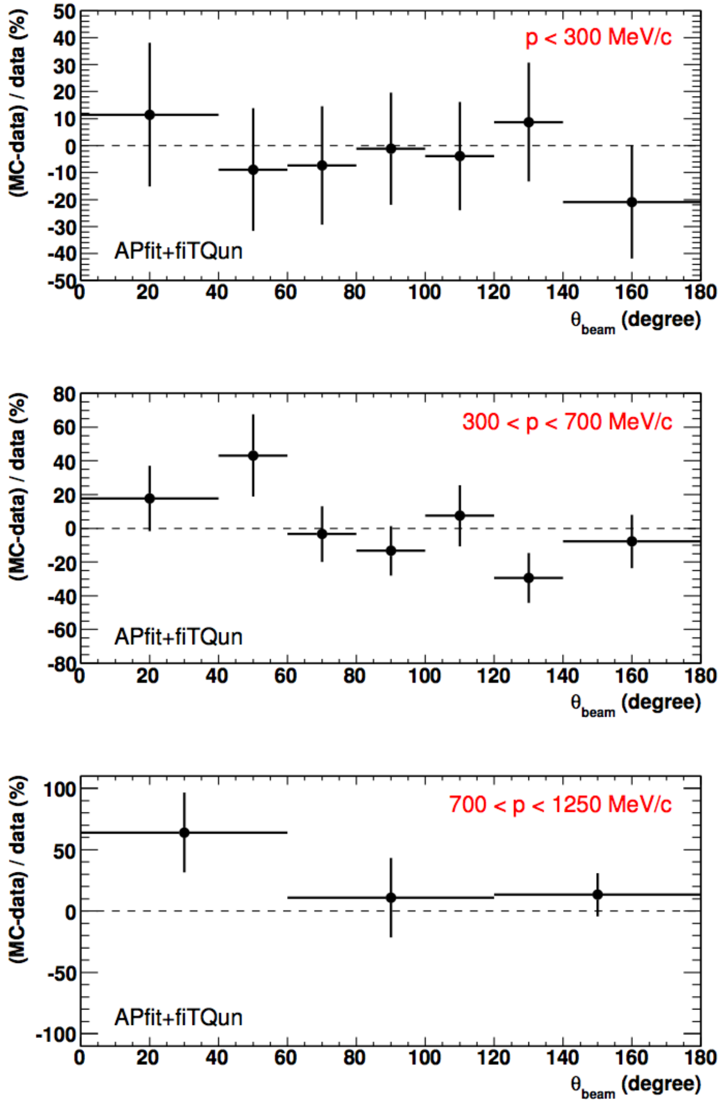
π0 mass

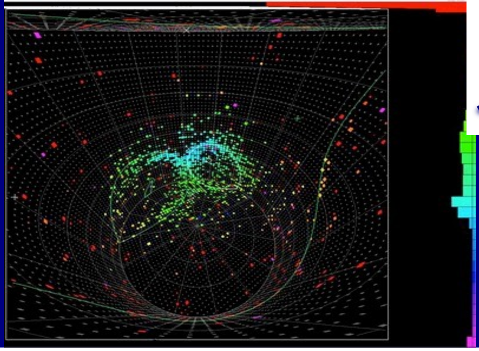


SK error w/ hybrid-π0

Correlated error:(MC-Data)/Data

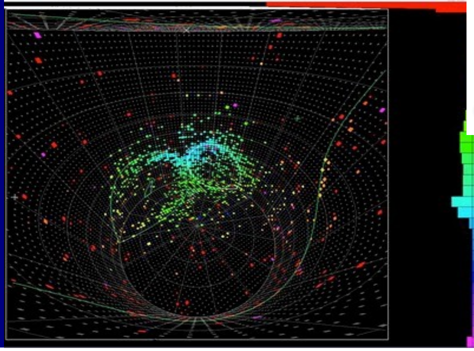
Uncorrelated error: Statistical uncertainties





Muon Neutrino
Dis-Appearance analysis

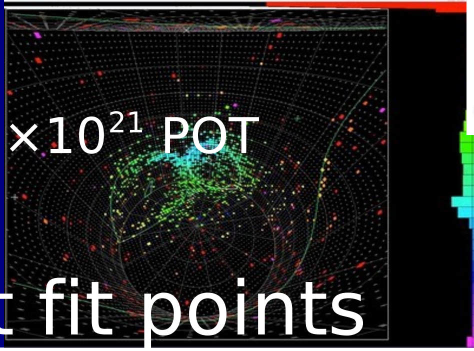
ν_μ Selection



RUN1+2+3 3.010×10^{20}POT	Data	MC Expectations w/ oscillation				
		MC total	$\nu_\mu+\nu_\mu$ CCQE	$\nu_\mu+\nu_\mu$ CC non-QE	$\nu_e+\nu_e$ CC	NC
True FV	-	296.67	45.22	110.25	8.31	132.89
FCFV	174	166.61	34.37	83.83	7.93	40.48
One-ring	88	83.56	32.47	34.52	5.03	11.55
μ-like	66	67.74	31.83	32.42	0.04	3.45
p_μ>200MeV/c	65	67.33	31.60	32.35	0.04	3.34
$N_{dcy\text{-}e}$<=1	58	57.78	31.25	23.29	0.03	3.21
Efficiency [%]	-	19.5	69.1	21.1	0.4	2.4

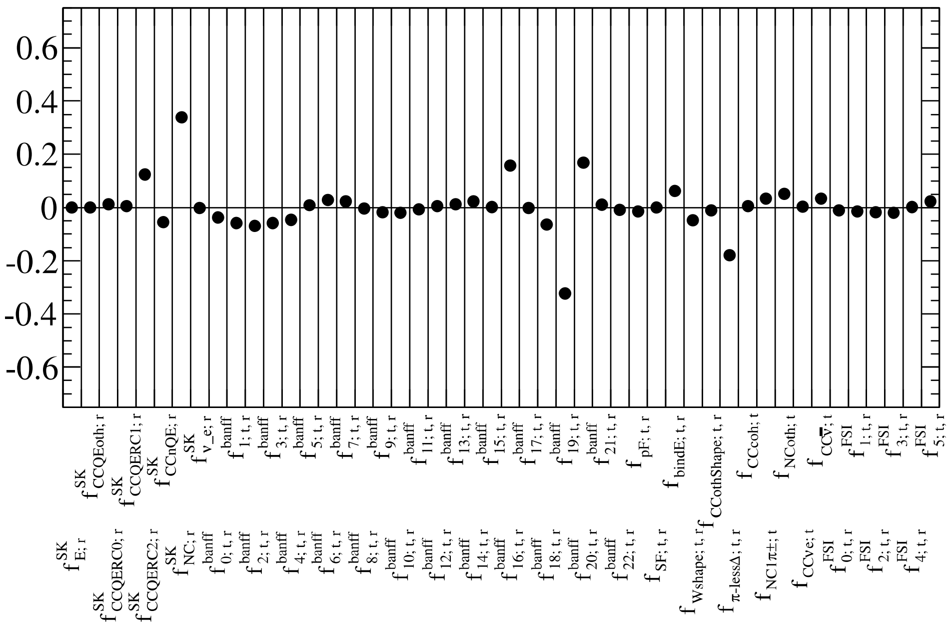
$\sin^2 2\theta_{23} = 1.0$ $\Delta m_{23}^2 = 2.4 \times 10^{-3}\ eV^2$

νμ disappearance results using 3.01×10^{21} POT

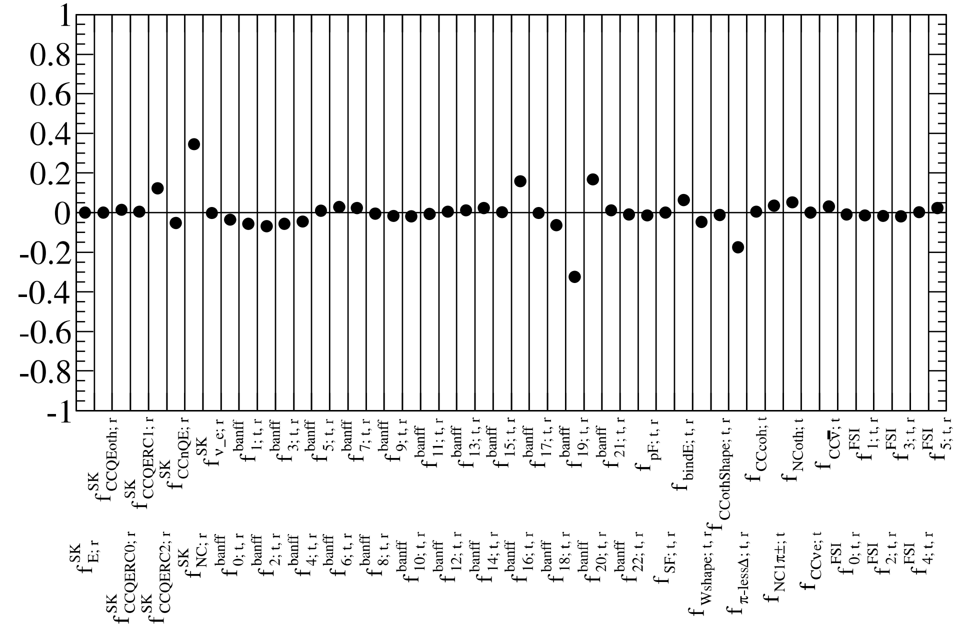


Pulls of 48 systematic errors @ best fit points

1st octant



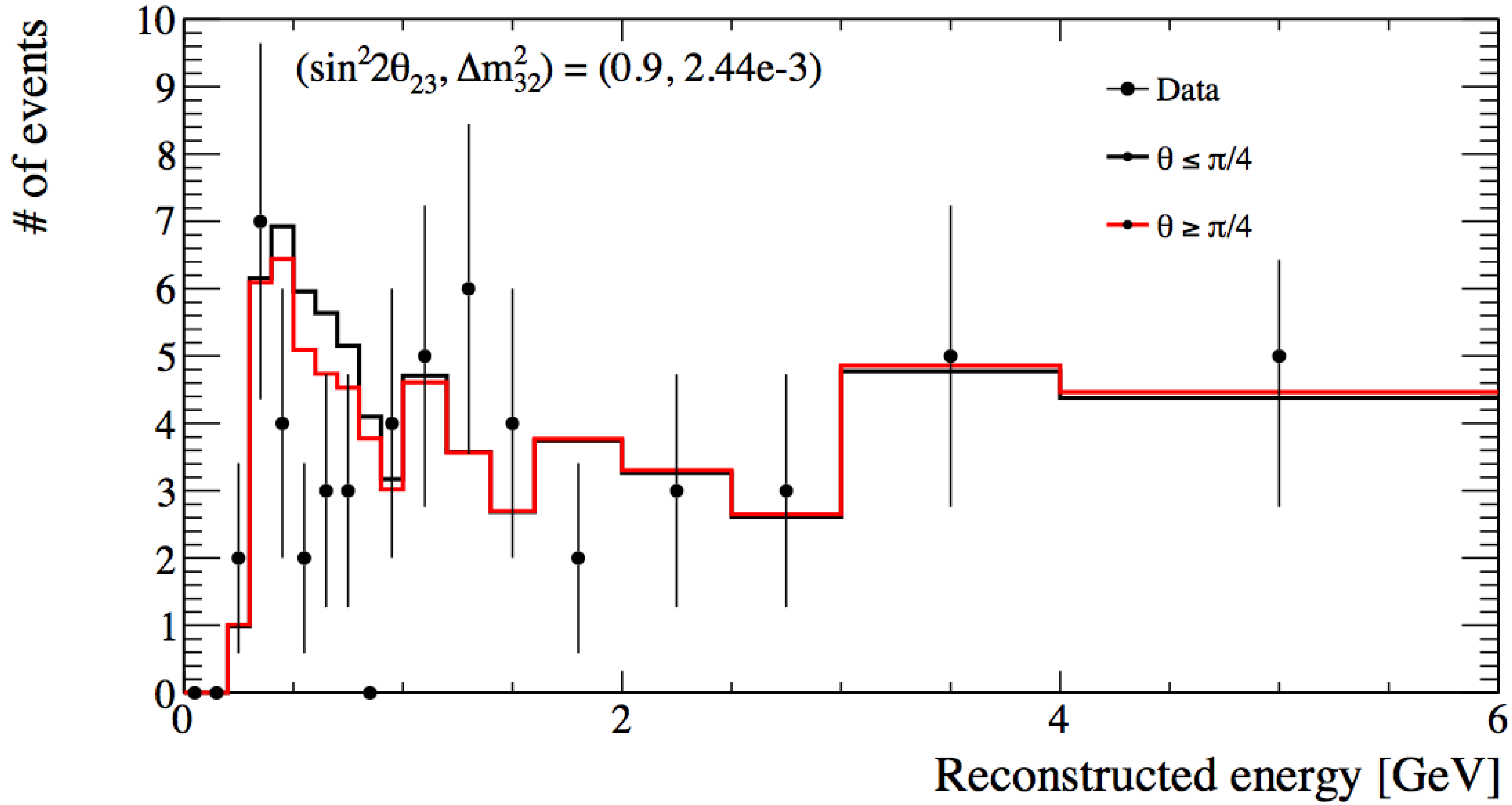
2nd octant



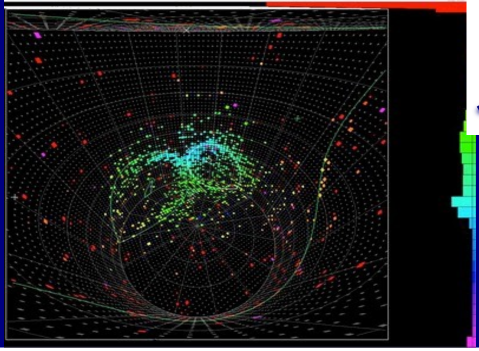
$$\mathrm{pull} = \frac{f_{\mathrm{best\ fit}} - f_{\mathrm{nominal}}}{\sigma_{\mathrm{best\ fit}}}$$

ν_μ disappearance results using 3.01×10^{21} POT

Fit spectra @ $(\sin^2 2\theta_{23}, \Delta m_{32}^2) = (0.9, 2.44\text{e-}3)$

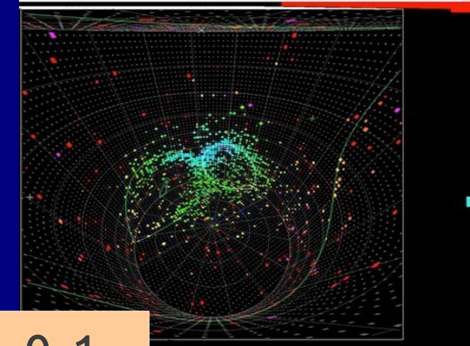


$$P(\nu_\mu \to \nu_\mu) \sim 1 - \left(\underbrace{\cos^4\theta_{13}\cdot\sin^2 2\theta_{23}}_{\text{Leading}} + \underbrace{\sin^2 2\theta_{13}\cdot\sin^2\theta_{23}}_{\text{Next-to-leading}}\right)\cdot\sin^2\frac{\Delta m^2_{31}\cdot L}{4E}$$



Electron Neutrino Appearance analysis

Expected # ν_e @ T2K

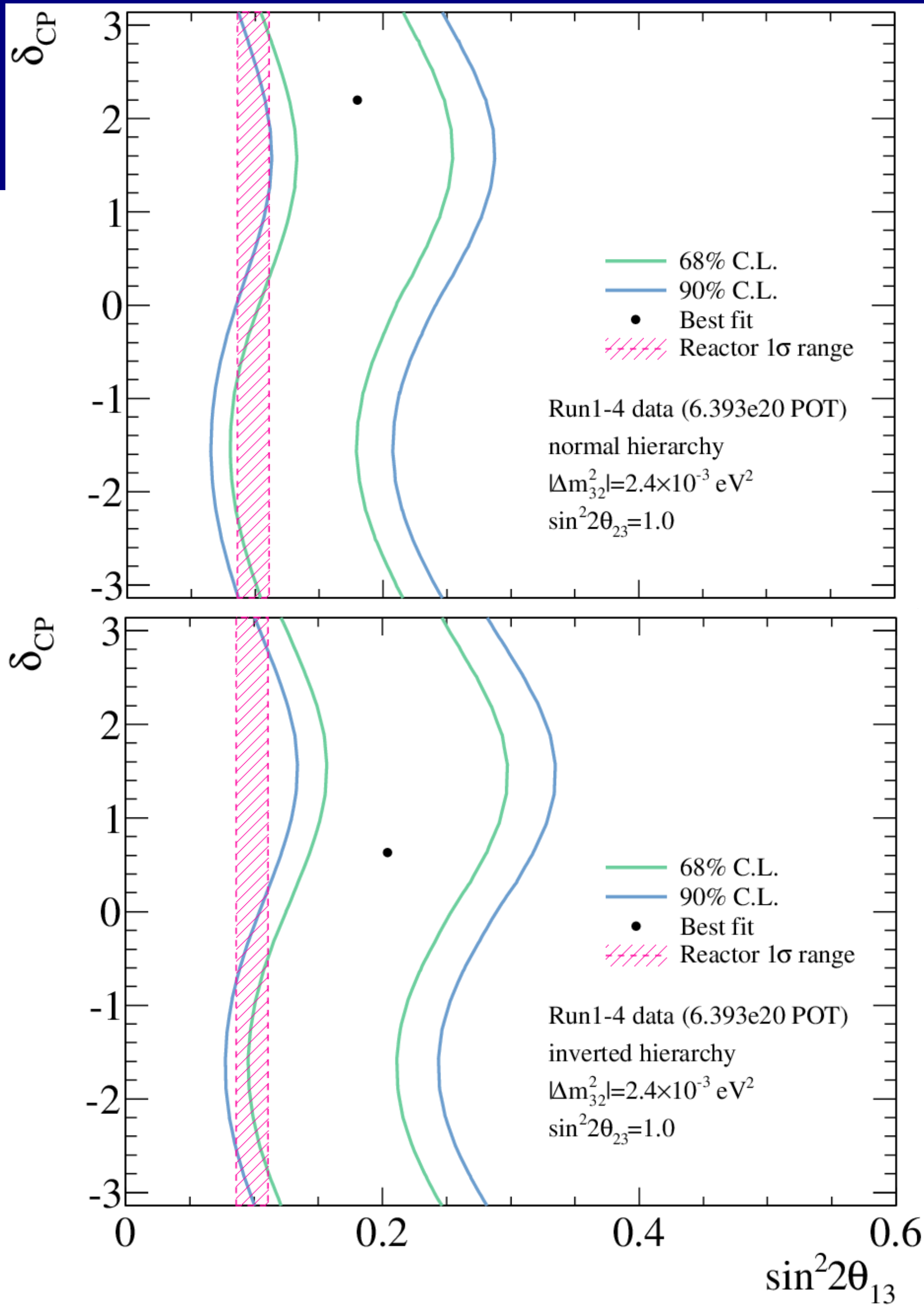


	$\sin^2 2\theta_{13} = 0.0$	$\sin^2 2\theta_{13} = 0.1$
ν_e signal	0.18	7.79
ν_e **background**	1.67	1.56
ν_μ **background**	1.21	1.21
ν_μ **background**	0.07	0.07
ν_e **background**	0.09	0.09
TOTAL	$\boxed{3.22}$	10.71

for 3.01 $\times 10^{20}$ POT

Systematic Errors	$\sin^2 2\theta_{13} = 0.0$	$\sin^2 2\theta_{13} = 0.1$
T2K Constrained Flux+Xsec	8.7%	5.7%
Xsec (External)	5.9%	7.5%
SK + FSI	7.7%	3.9%
TOTAL	13.4%	10.3%

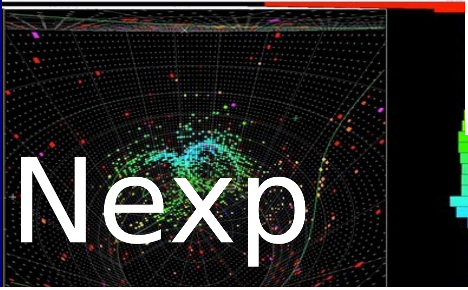
2D Contour of δCP vs. sin22θ13 with reactor result



In these plots, the contours are calculated in 2D space.

Pink band represents PDG2012 reactor average value of sin22θ13. (0.098±0.013)

Systematic errors for Nexp

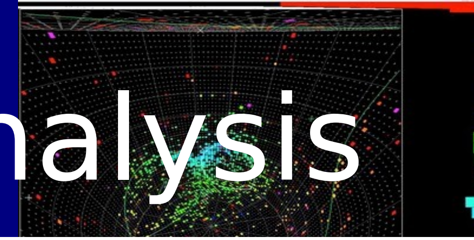


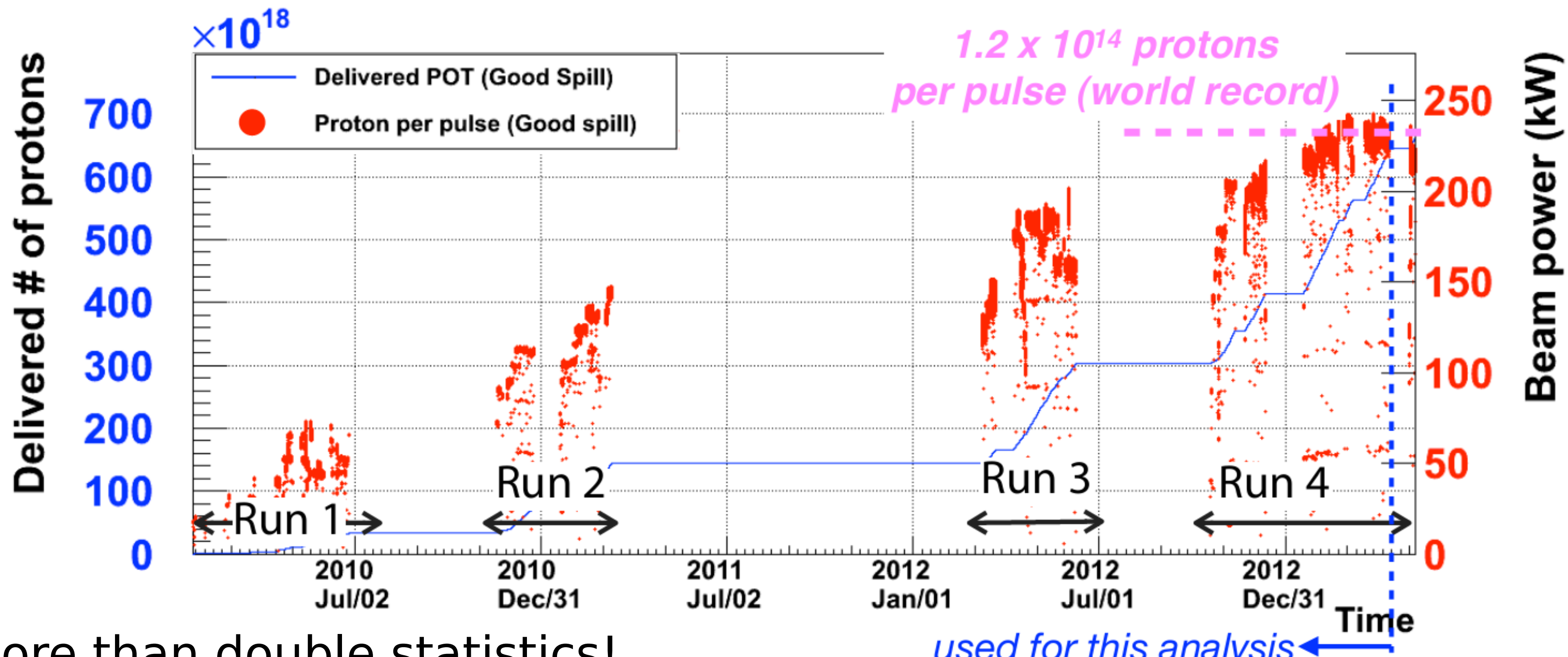
Error source	$\sin^2 2\theta_{13} = 0$				$\sin^2 2\theta_{13} = 0.1$			
	w/o ND280 fit		w/ ND280 fit		w/o ND280 fit		w/ ND280 fit	
Beam only	10.6	10.8	7.3	7.5	11.6	11.9	7.5	8.1
M_A^{QE}	15.6	9.5	2.4	4.0	21.5	16.3	3.2	6.7
M_A^{RES}	7.2	4.5	2.1	3.9	3.3	2.0	0.9	1.8
CCQE norm. ($E_\nu < 1.5$ GeV)	7.1	4.9	4.8	3.8	9.3	7.9	6.3	6.2
CC1π norm. ($E_\nu < 2.5$ GeV)	4.9	5.1	2.4	3.5	4.2	5.2	2.0	3.5
NC1π^0 norm.	2.7	7.9	1.9	7.3	0.6	2.3	0.4	2.2
CC other shape	0.3	0.2	0.3	0.2	0.1	0.1	0.1	0.1
Spectral Function	4.7	3.3	4.8	3.3	6.0	5.7	6.0	5.7
p_F	0.1	0.3	0.1	0.3	0.1	0.0	0.1	0.0
CC coh. norm.	0.3	0.2	0.3	0.2	0.3	0.2	0.2	0.2
NC coh. norm.	1.1	2.1	1.1	2.0	0.3	0.6	0.2	0.6
NC other norm.	2.3	2.6	2.2	2.6	0.5	0.8	0.5	0.8
$\sigma_{\nu_e}/\sigma_{\nu_\mu}$	2.4	1.8	2.4	1.8	2.9	2.6	2.9	2.6
W shape	1.0	1.9	1.0	1.9	0.2	0.8	0.2	0.8
pion-less Δ decay	3.3	0.5	3.1	0.5	3.7	3.2	3.5	3.2
SK detector eff.	5.7	6.8	5.6	6.8	2.4	3.0	2.4	3.0
FSI	3.0	2.9	3.0	2.9	2.3	2.3	2.3	2.3
PN	3.6	0.0	3.5	0.0	0.8	0.0	0.8	0.0
SK momentum scale	1.5	21.0	1.5	13.0	0.6	24.2	0.6	9.9
Total	24.5		11.1		28.1		8.8	

Blue is 2012 result. All are quoted as % error.

9

Changes from 2012 Analysis

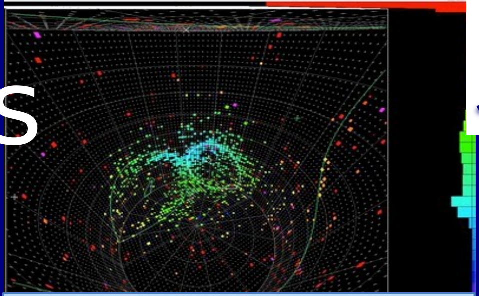




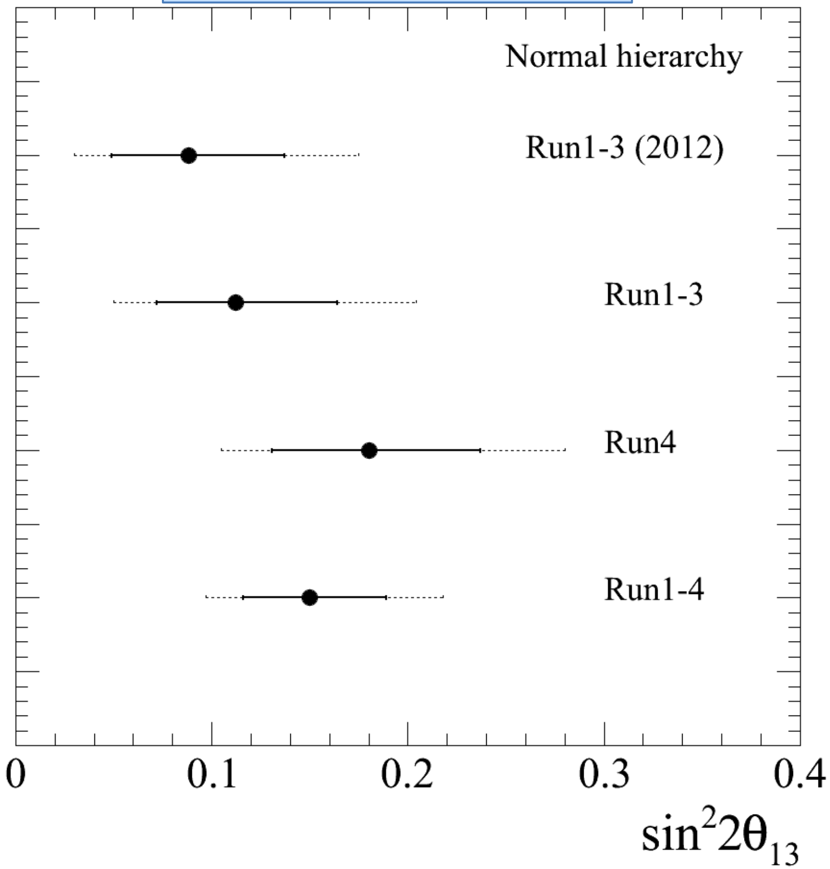
(partial data set until Apr 12)

- More than double statistics!
  - 2012 analysis (Run1+2+3): 3.010×1020 POT, Nevents = 11
  - 2013 analysis (Run1+2+3+4(~Apr 12)): 6.393×10^{20} POT, Nevents = 11+17 = 28
- The background rejection cut is improved by using a new SK reconstruction algorithm. BG events reduced from 6.4 to 4.6!
- Near detector measurement is improved by having new event categories which can further constraint the neutrino beam flux and cross section systematic errors.

• Current and Previous Results

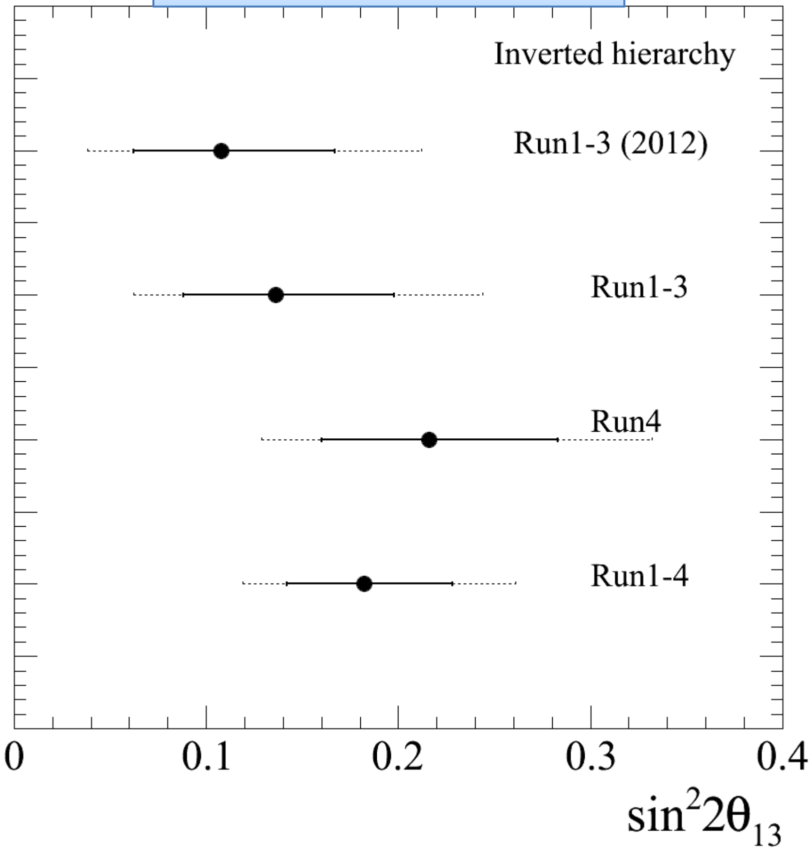


Normal hierarchy



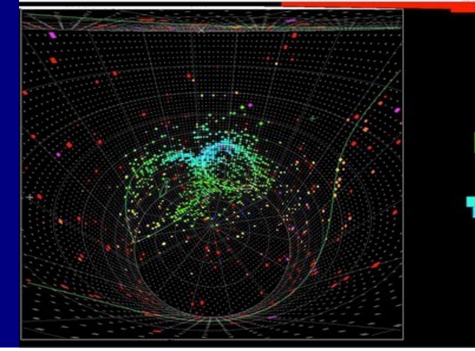
—68% C.L.
---90% C.L.

Inverted hierarchy



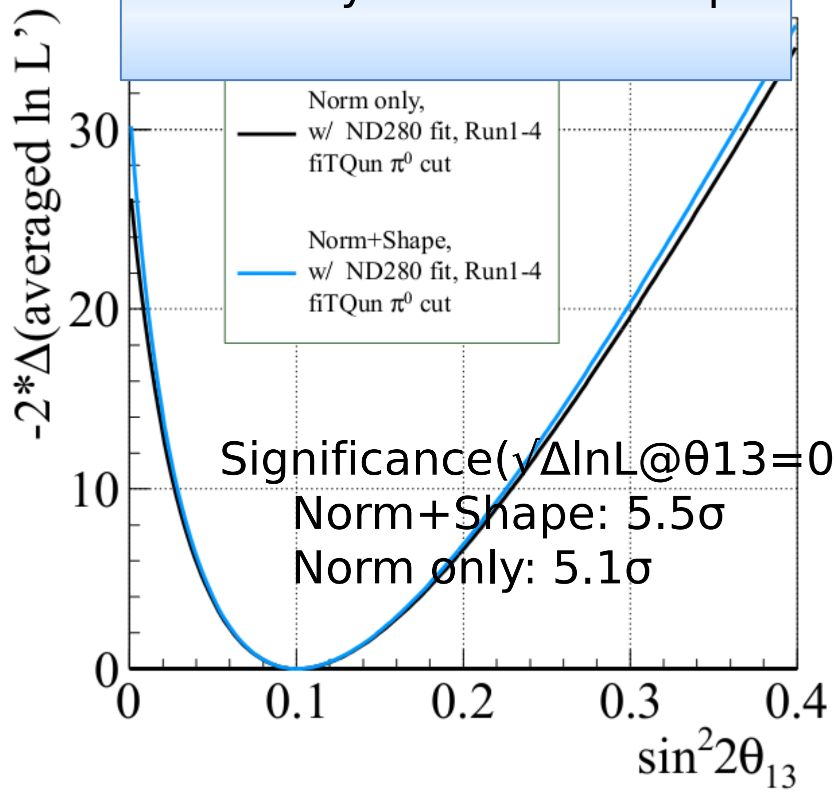
- Run 4 best fit value is higher than the others.
- Run1-3 (2012) looks different from Run1-3, because:
  - -Npred decreased by using new Super-K reconstruction, while Nobs did not change.
  - -Npred decreased with Run 1-4 near detector fit.

Sensitivity checks



We fit the toy MC experiments (true sin22θ13=0.1) to check the sensitivity.
The averaged lnL curves ↓ are generated by averaging 4000 toy experiments.

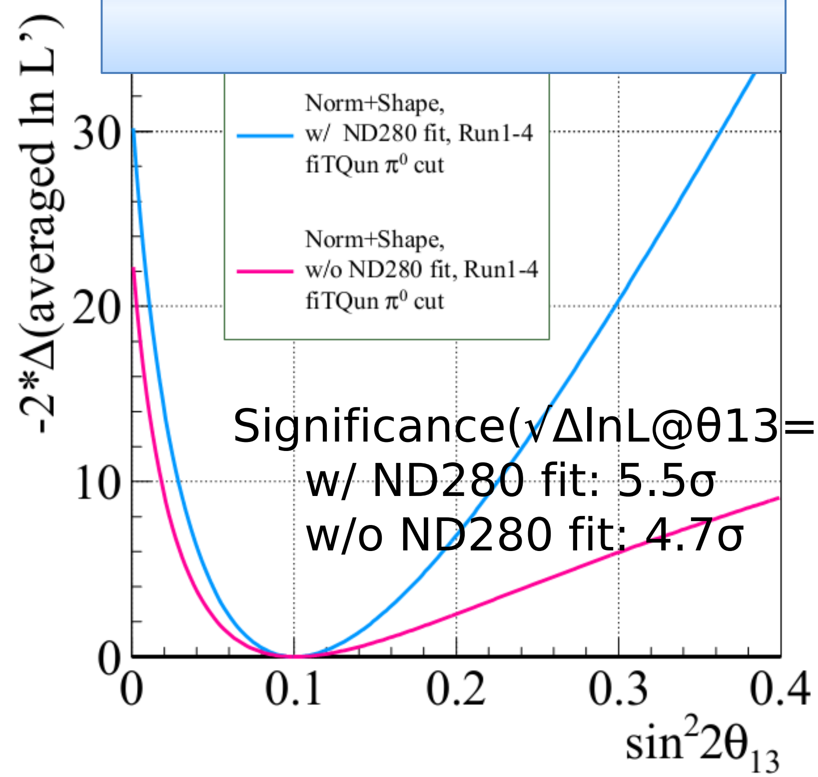
Norm only & Norm + Shape



Significance(√ΔlnL@θ13=0):
Norm+Shape: 5.5σ
Norm only: 5.1σ

Effect of using shape information is not significant but important.

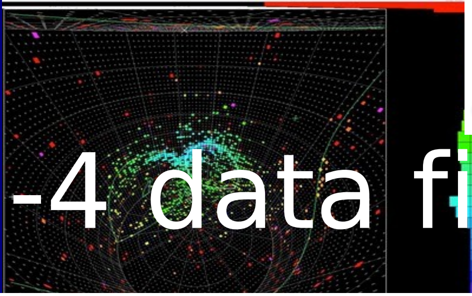
w/ ND280 fit & w/o ND280 fit

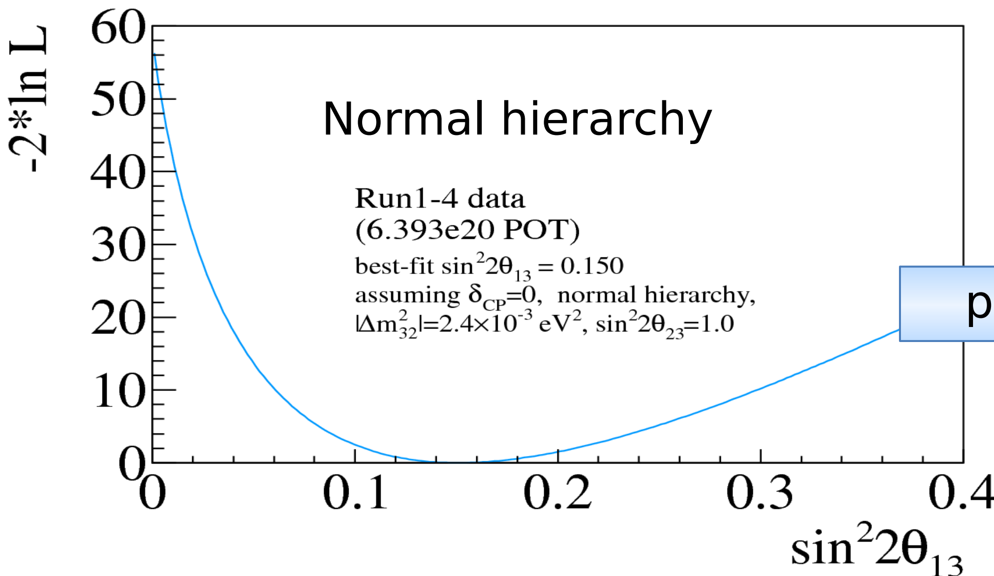


Significance(√ΔlnL@θ13=0):
w/ ND280 fit: 5.5σ
w/o ND280 fit: 4.7σ

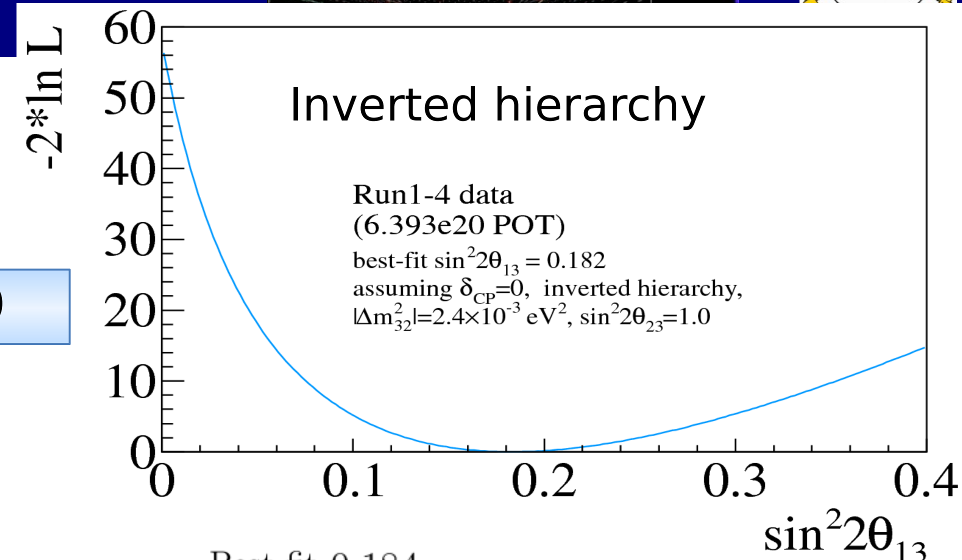
ND280 fit makes relatively large improvement.

Likelihood curves for Run1-4 data fit

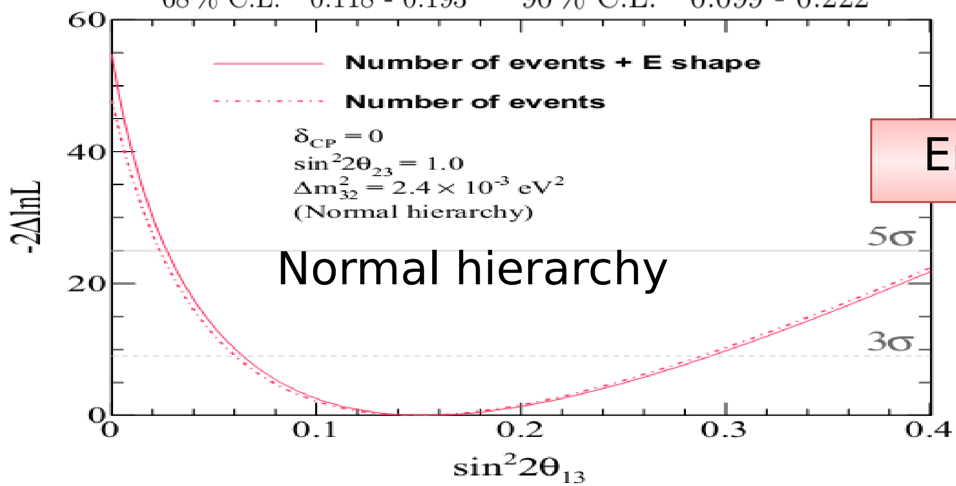




p-θ

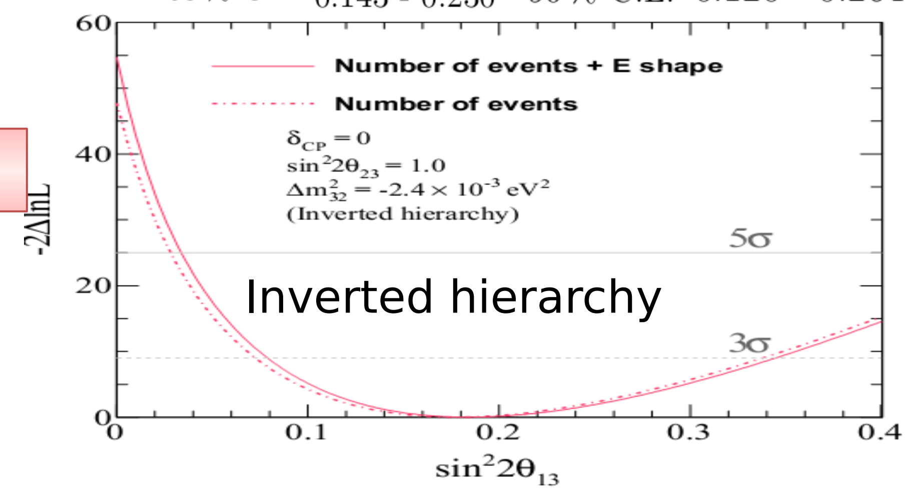


Best fit 0.152
68 % C.L. 0.118 - 0.193 90 % C.L. 0.099 - 0.222



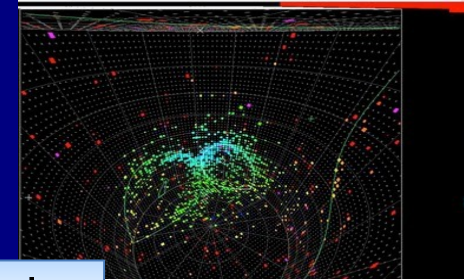
Erec

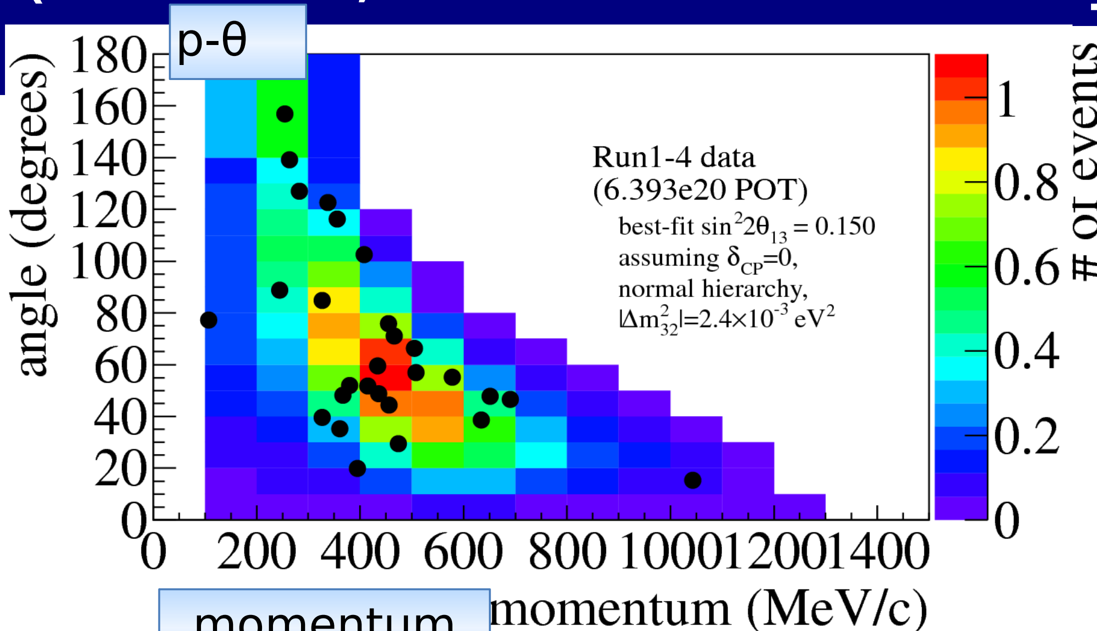
Best fit 0.184
68 % C.L. 0.143 - 0.230 90 % C.L. 0.120 - 0.264

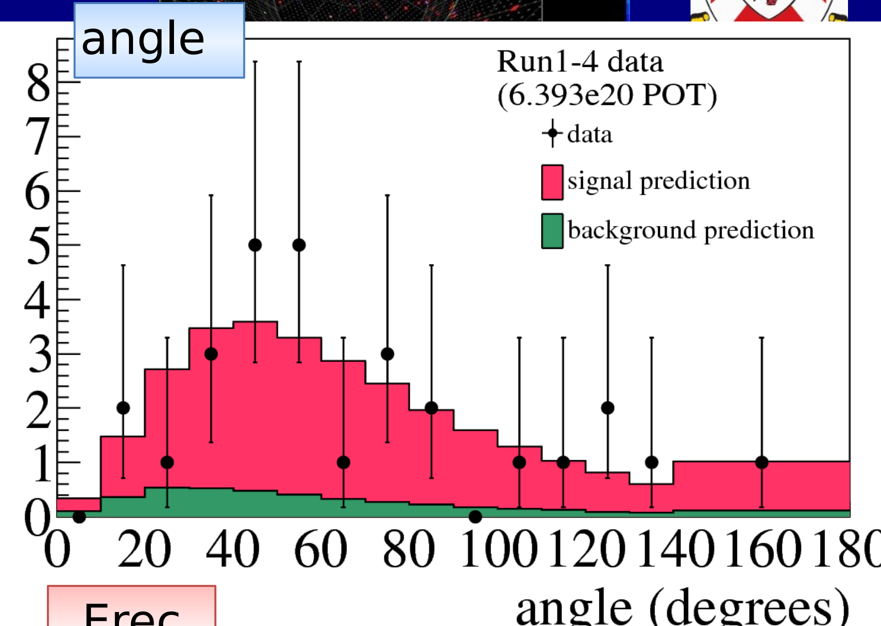


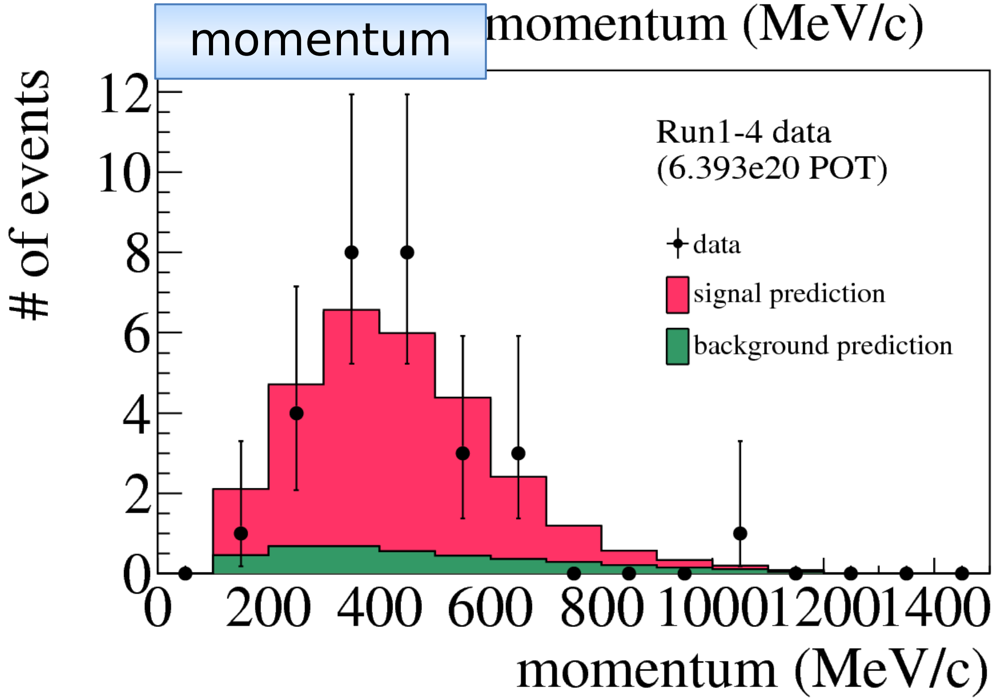
(summary table will be shown later.)

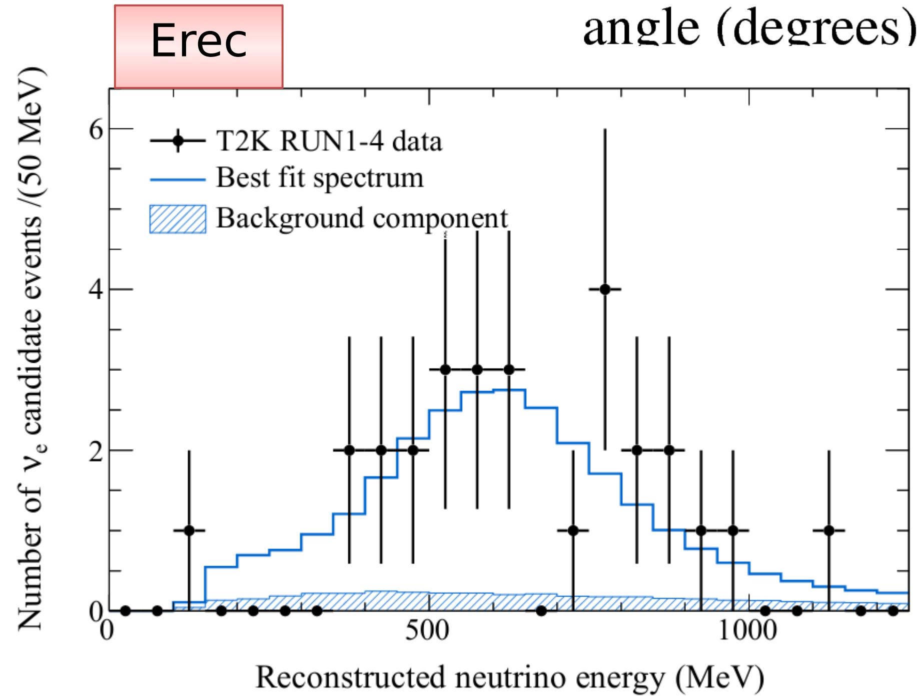
Best fit distributions (Run1-4, normal hierarchy)



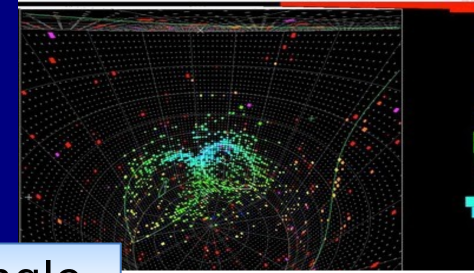


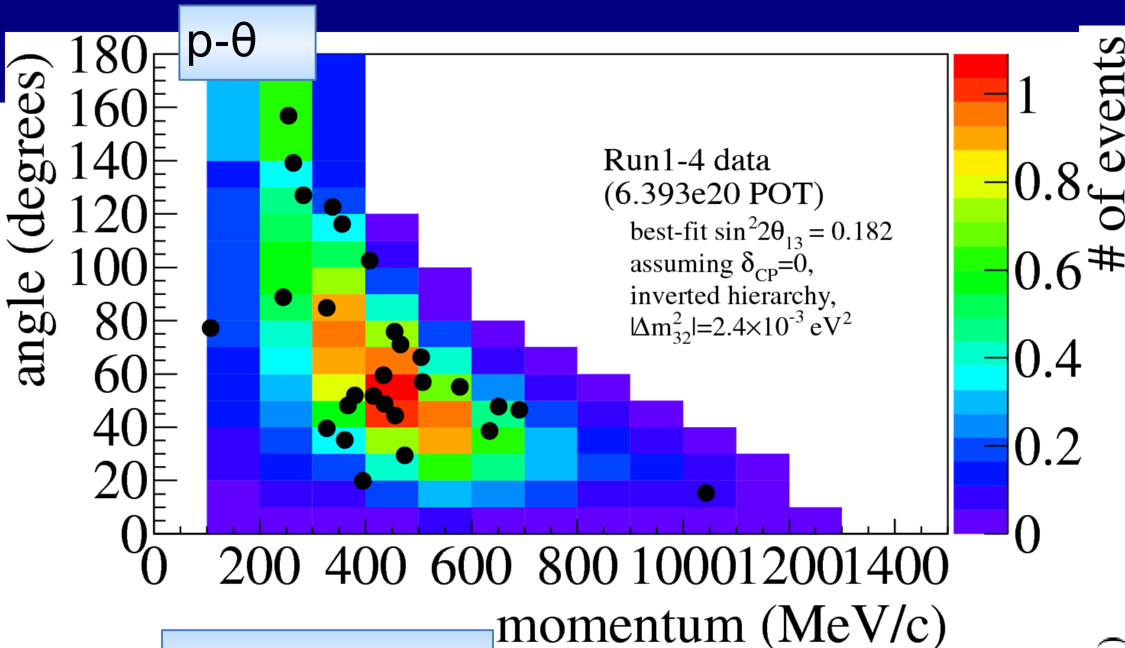


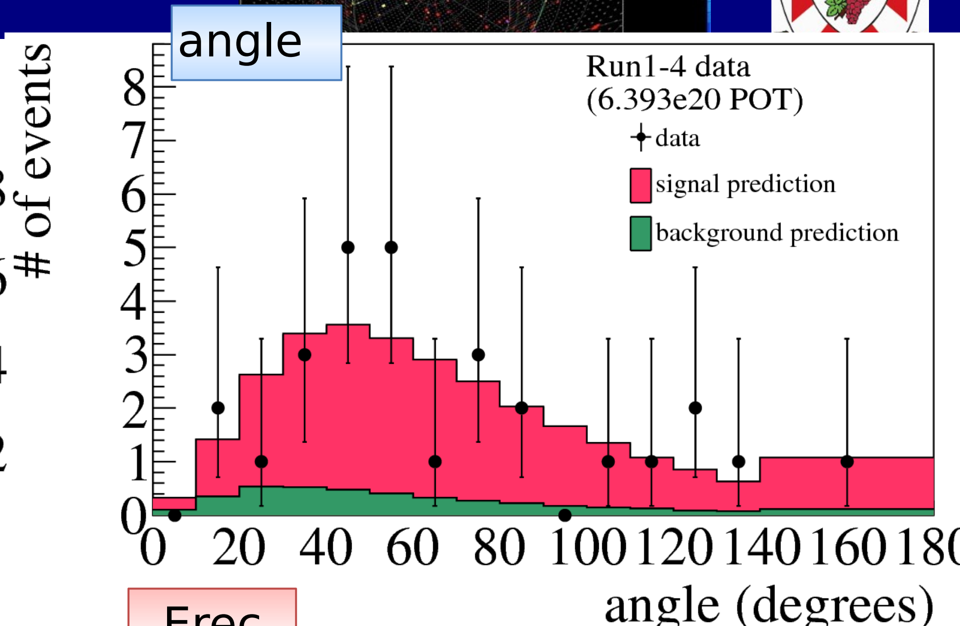


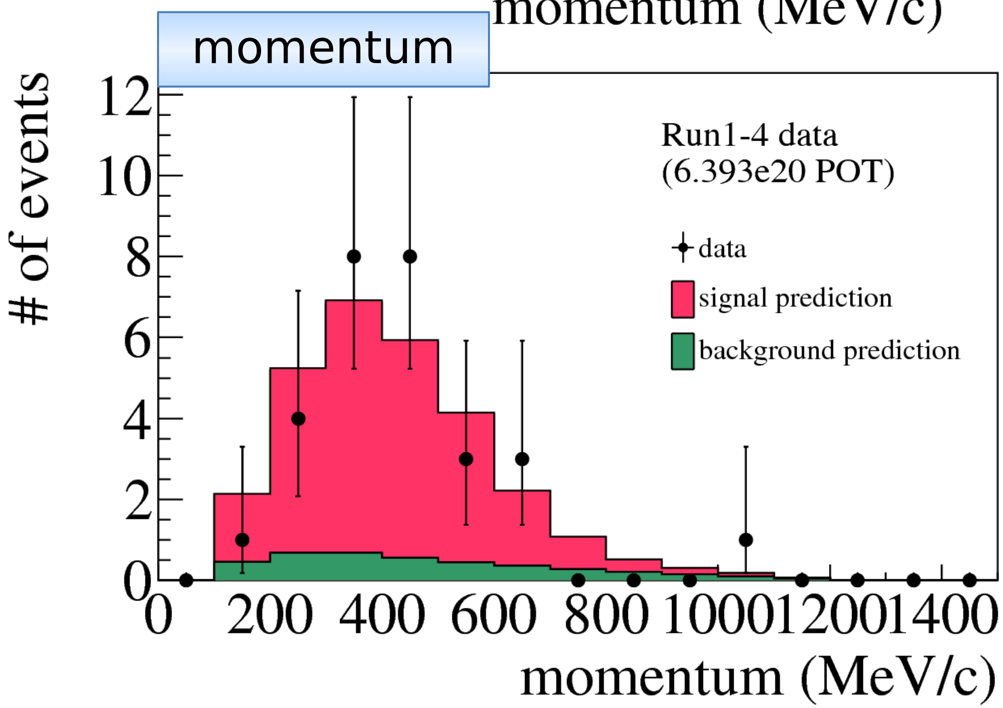


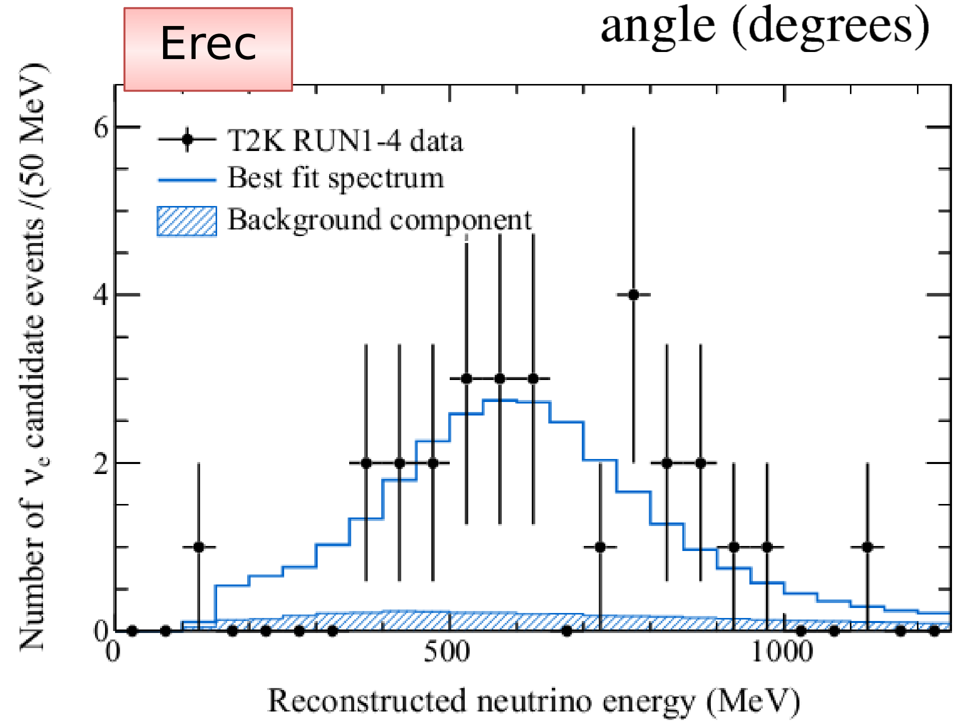
Best fit distributions (Run1-4, inverted hierarchy)



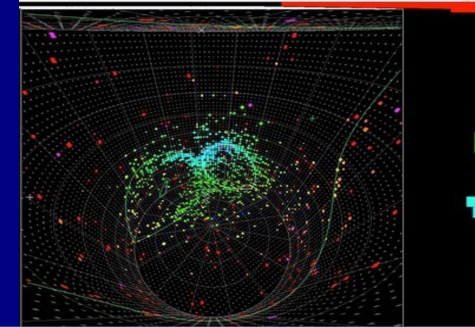




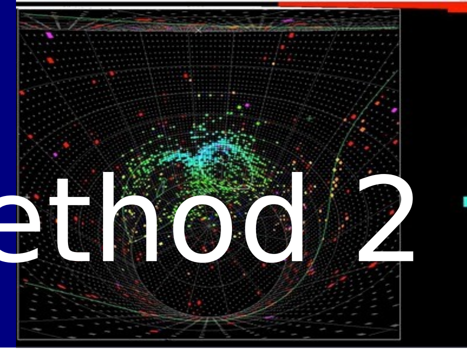




Fit summary table



	Run1-4 (p-θ)	Run1-4 (Erec)	Run4 only	Run1-3 (2013 analysis)	Run1-3 (2012 analysis)
POT	6.39e20	6.39e20	3.38e20	3.01e20	3.01e20
Observed number of events	28	28	17	11	11
<u>Normal hierarchy</u> Best fit 90% C.L. 68% C.L.	 0.150 0.097 - 0.218 0.116 - 0.189	 0.152 0.099 - 0.222 0.118 - 0.193	 0.180 0.105 - 0.280 0.131 - 0.237	 0.112 0.050 - 0.204 0.072 - 0.164	 0.088 0.030 - 0.175 0.049 - 0.137
<u>Inverted hierarchy</u> Best fit 90% C.L. 68% C.L.	 0.182 0.119 - 0.261 0.142 - 0.228	 0.184 0.120 - 0.264 0.143 - 0.230	 0.216 0.129 - 0.332 0.160 - 0.283	 0.136 0.062 - 0.244 0.088 - 0.198	 0.108 0.038 - 0.212 0.062 - 0.167

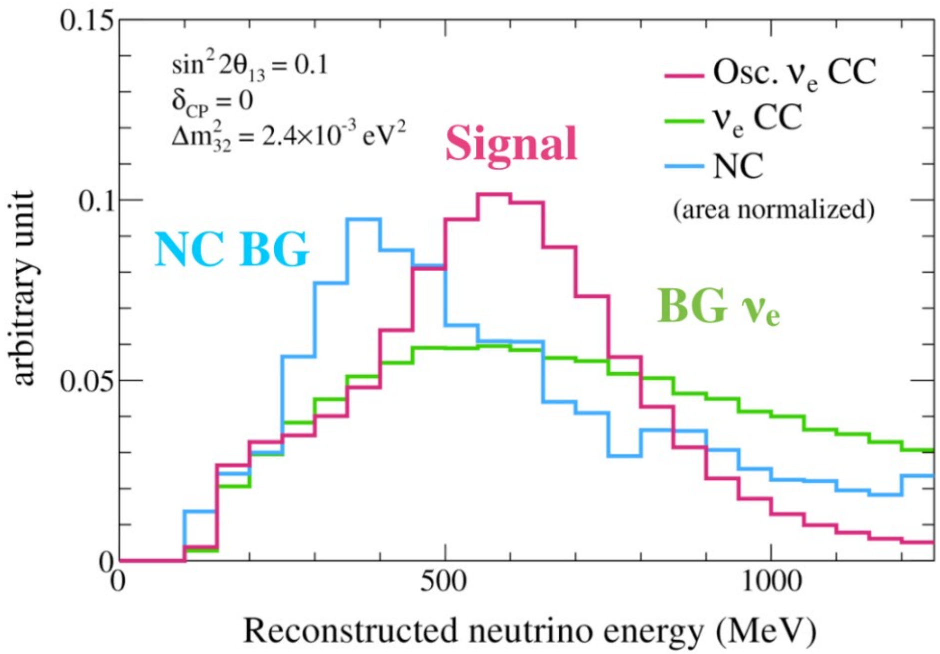


Oscillation analysis method 2

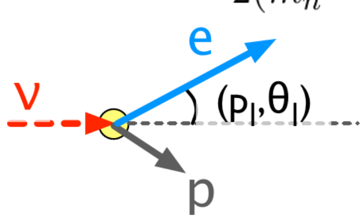
Method 2: Rate + reconstructed Eν shape (1D)

assuming
$|\Delta m^2_{32}|$=2.4×10-3 eV2
δCP=0, $\sin^2 2\theta_{23}$=1,
Normal hierarchy

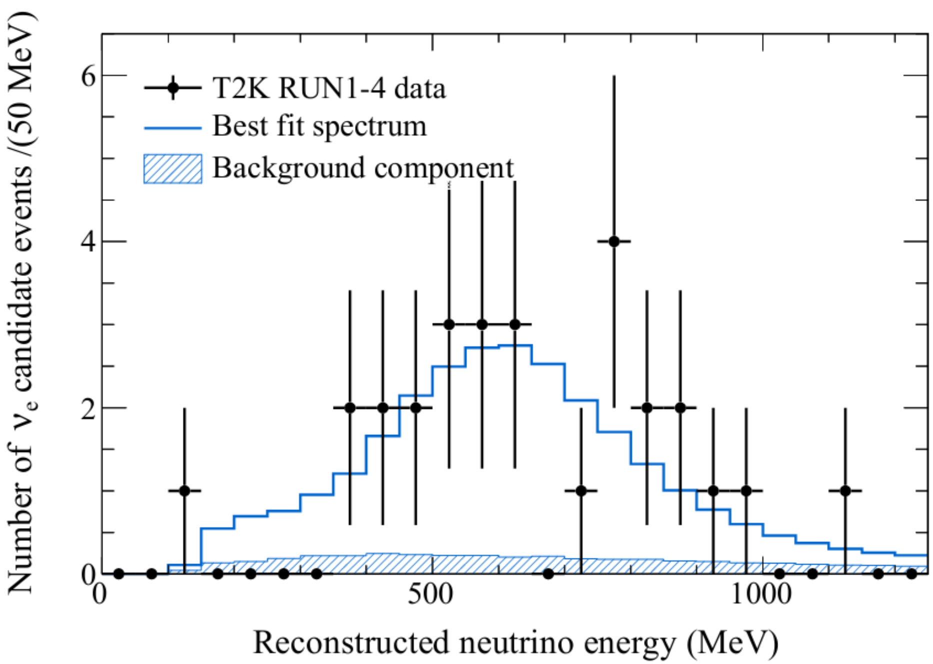
Fit data to the reconstructed energy distribution



$$E^{rec} = \frac{m_p^2 - (m_n - E_b)^2 - m_e^2 + 2(m_n - E_b)E_e}{2(m_n - E_b - E_e + p_e \cos\theta_e)}$$



Fit result



best fit w/ 68% C.L. error:

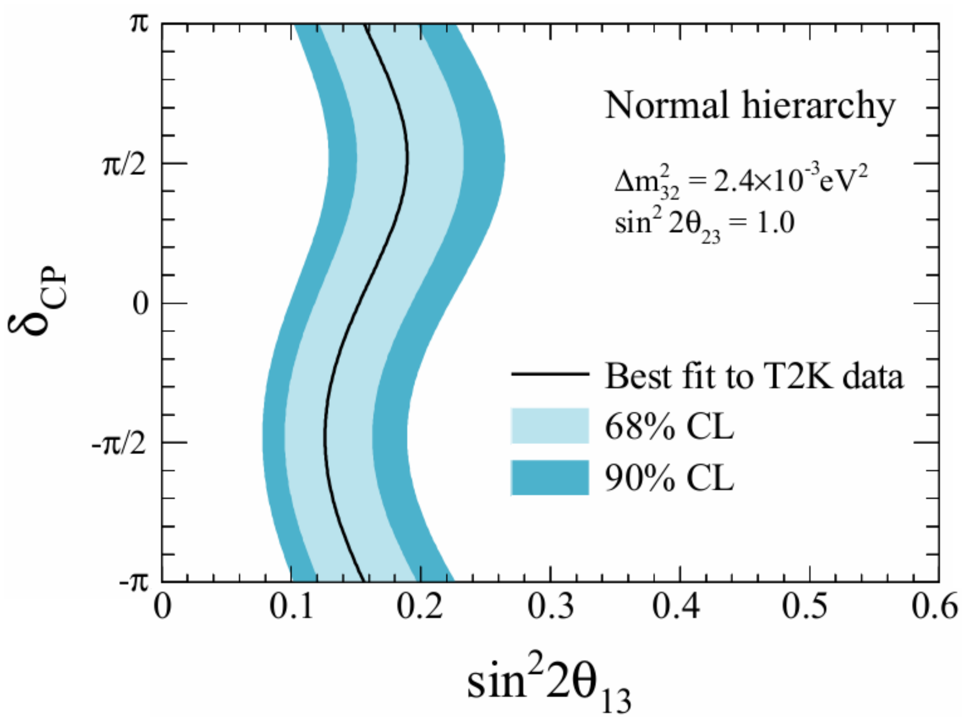
$$\sin^2 2\theta_{13} = 0.152^{+0.041}_{-0.034}$$

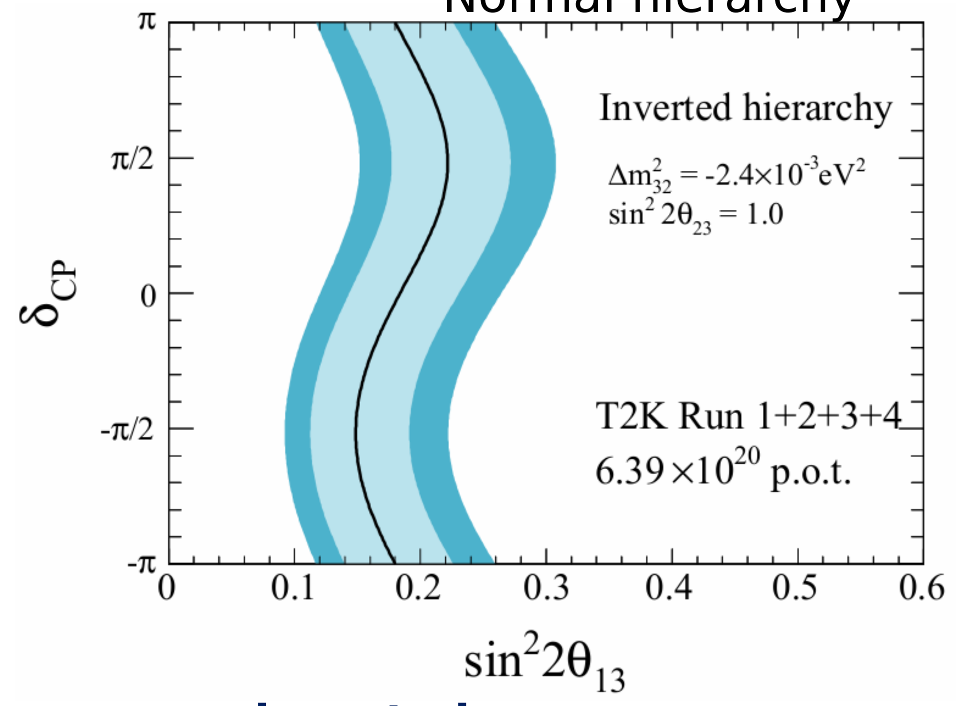
Oscillation analysis method 2

Method 2: Rate + reconstructed Eν shape (1D)

assuming $|\Delta m^2_{32}|=2.4\times10\text{-}3$ eV2
δCP=0, $\sin^2 2\theta_{23}=1$,
Normal hierarchy

Allowed region of $\sin^2 2\theta_{13}$ for each value of δCP





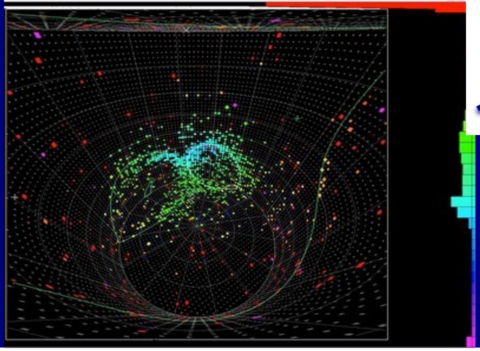
best fit w/ 68% C.L. error @ δCP=0

normal hierarchy:

$$\sin^2 2\theta_{13} = 0.152^{+0.041}_{-0.034}$$

inverted hierarchy:

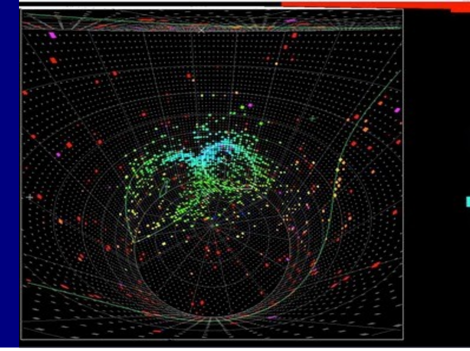
$$\sin^2 2\theta_{13} = 0.184^{+0.046}_{-0.041}$$



J-PARC Accelerator Upgrades

Slides from Koseki-san
at “Snowmass” April meeting

JPARC Power Upgrade



JFY	2011	2012	2013	2014	2015	2016	2017
			Li. upgrade				
FX power [kW] SX power：User op.（study）[kW]	150 3 (10)	200 10 (50)	~ 300 ＜50	400 50 (100)			750 100
Cycle time of main magnet PS **New magnet PS for high rep.**	3.04 s	2.56–2.48 s R&D	2.48–2.40 s		Manufacture installation/test		1.3 s
Present RF system **New high gradient rf system**	Install. #7,8	Install. #9 R&D		Manufacture installation/test			
Ring collimators	Additional shields	Add. shields & collimators (2kW)	Add. shields & collimators (3.5kW)				
Injection system **FX system**	New injection kicker	Kicker PS improvement、Septum1 manufacture /test LF septum, PS for HF septa manufacture /test					

Upgrade plan of linac

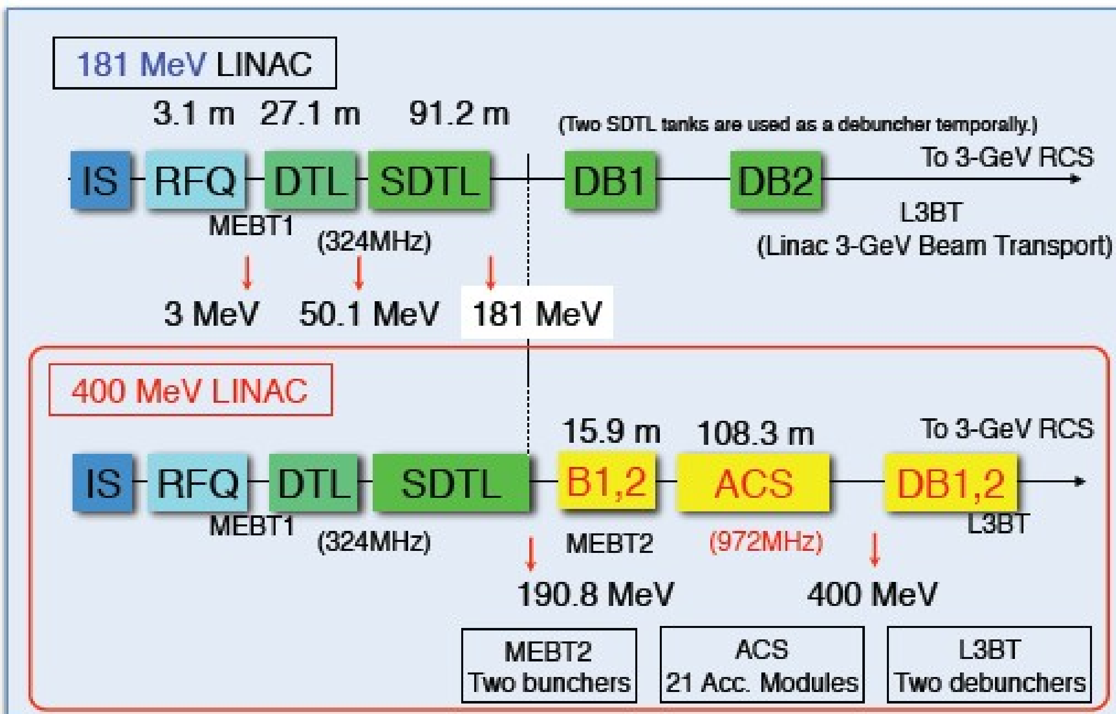
The design specification of the J-PARC facility (e.g. 1MW@RCS, 0.75MW@MR) cannot be realized with the present 181 MeV/30 mA linac.

For beam energy (Small emittance beam for the RCS injection) :

New accelerating structure, ACS(Annular Coupled Structure linac) will be installed to increase the extracted beam energy of the linac from 181 MeV to 400 MeV. Power supplies of RCS injection magnets will also be replaced for adopting 400 MeV injection beam.

For peak beam current :

Front-end part (IS+RFQ) will be replaced for increasing peak current from 30 mA to 50 mA.



New ion source using rf antenna (Collaboration with SNS)

ACS modules are waiting for installation

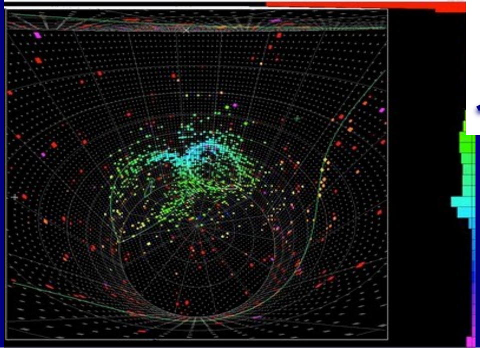
T2K

Mid-term plan of MR

FX: We adopt the high repetition rate scheme to achieve the design beam intensity, 750 kW. Rep. rate will be increased from ~ 0.4 Hz to ~1 Hz by replacing magnet PS's and RF cavities.
SX: A part of SUS vacuum chambers will be replaced with Ti chambers to reduce residual radiation dose. After the replacement, 50 kW operation for users will be started. Beam power will be increased toward 100 kW carefully watching the residual activity. Local shields will also be installed if necessary.

JFY	2011	2012	2013	2014	2015	2016	2017
			LI. upgrade				
FX power [kW] SX power : User op. (study) [kW]	150 3 (10)	200 10 (50)	~ 300 <50	400 50 (100)	→	→	750 100
Cycle time of main magnet PS New magnet PS for high rep.	3.04 s R&D →	2.56–2.48 s R&D →	2.48–2.40 s R&D →	Manufacture installation/test →	Manufacture installation/test →	Manufacture installation/test →	1.3 s
Present RF system New high gradient rf system	Install. #7,8 R&D →	Install. #9 R&D →	R&D → Manufacture installation/test	Manufacture installation/test →	Manufacture installation/test →		
Ring collimators	Additional shields	Add. shields & collimators (2kW)	Add. shields & collimators (3.5kW)				
Injection system FX system	New inj. kicker	Kicker PS improvement, Septum1 manufacture /test LF septum, PS for HF septa manufacture /test →	Kicker PS improvement, Septum1 manufacture /test LF septum, PS for HF septa manufacture /test →	Kicker PS improvement, Septum1 manufacture /test LF septum, PS for HF septa manufacture /test →			
SX collimator / Local shields	SX collimator			Local sheilds →	Local sheilds →	Local sheilds →	
Ti ducts and SX devices with Ti chamber		Septum endplate	ESS, Beam ducts				

The new PS requires additional budget of ~ 60 oku-Yen. The budget request will be submitted to the government in 2014-2016.



FUTURE SENSITIVITY

$\nu_\mu \to \nu_e$ Oscillation Probability

Precise measurement of $\sin^2 2\theta_{13}$ enhances the T2K sensitivity to δ_{CP} and the θ_{23} octant:

(ν_μ disappearance measures $\sin^2 2\theta_{23}$ and cannot distinguish the octant alone)

$$P(\nu_\mu \to \nu_e) = 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2\Phi_{31}\left(1 + \frac{2a}{\Delta m_{31}^2}(1-2S_{13}^2)\right) \quad \to \text{Leading, matter effect}$$

$$+ 8C_{13}^2 S_{12} S_{13} S_{23}(C_{12}C_{23}\cos\delta - S_{12}S_{13}S_{23})\cos\Phi_{32}\sin\Phi_{31}\sin\Phi_{21} \quad \to \text{CP conserving}$$

$$- 8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin\Phi_{32}\sin_{31}\sin\Phi_{21} \quad \to \text{CP violating}$$

$$+ 4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12}C_{23}S_{12}S_{23}S_{13}\cos\delta)\sin^2\Phi_{21} \quad \to \text{Solar}$$

$$- 8C_{13}^2 S_{13}^2 S_{23}^2 (1-2S_{13}^2)\frac{aL}{4E}\cos\Phi_{32}\sin\Phi_{31} \quad \to \text{Matter effect}$$

($C_{ij} = \cos\theta_{ij}$, $S_{ij} = \sin\theta_{ij}$, $\Phi_{ij} = \Delta m_{ij}^2 L/4E$)

- δ_{CP} completely unknown
- MH completely unknown
- $\theta_{12} = 33.6^\circ \pm 1.0^\circ$
- $\theta_{23} = 45^\circ \pm 6^\circ$ (90% C.L.) – is θ_{23} maximal?
- $\theta_{13} = 9.1^\circ \pm 0.6^\circ$ – from reactor

T2K Future Sensitivity Study

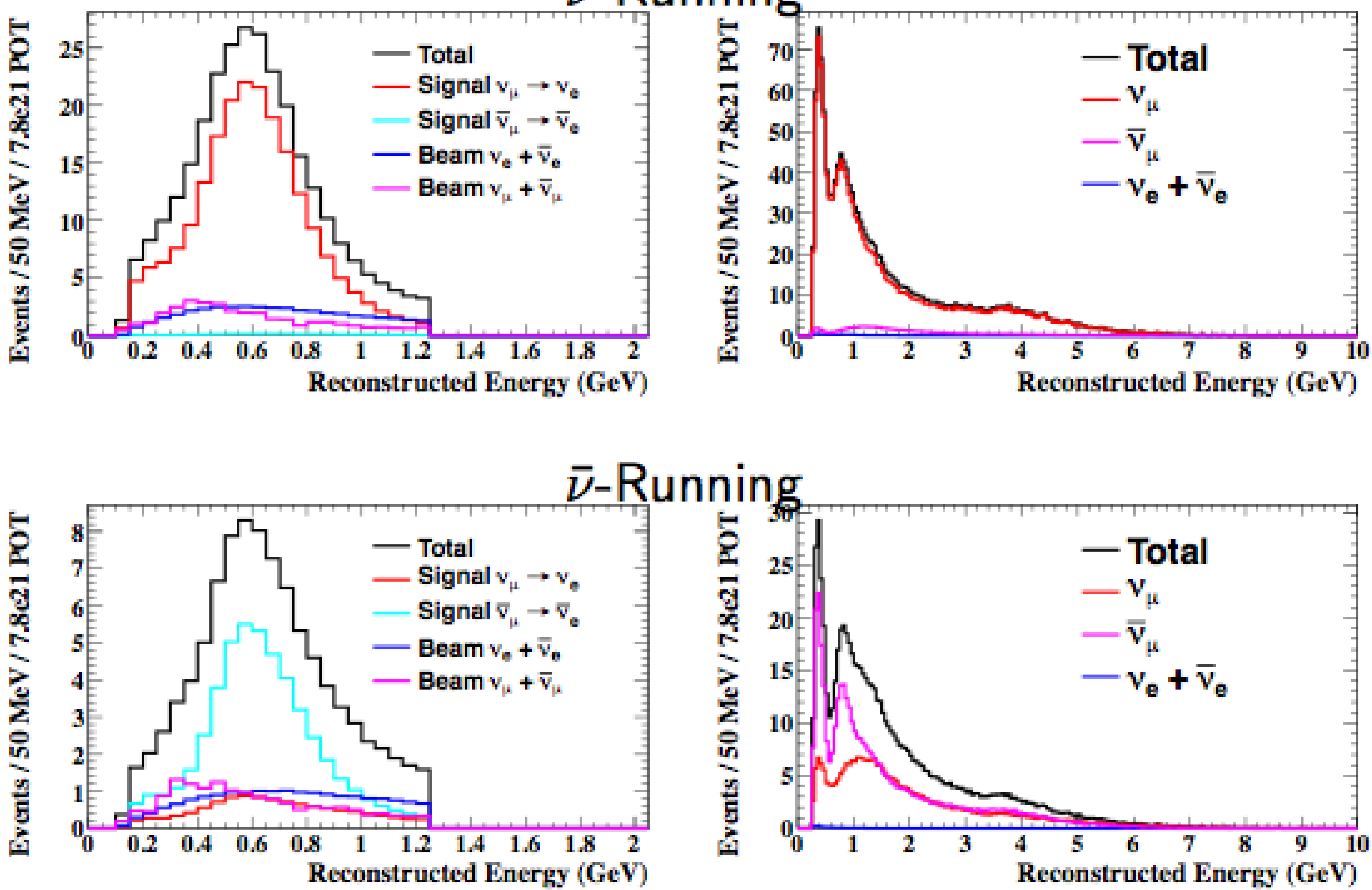
- T2K combined 3 flavor appearance + disappearance fits
  - At full T2K statistics – 7.8×10^{21} POT
  - Simultaneously fit MC SK reconstructed energy spectra for ν_e, ν_μ, $\bar{\nu}_e$, and $\bar{\nu}_\mu$
  - Maximum likelihood fit
  - Uncertainties on $\sin^2 2\theta_{13}$, δ_{CP}, $\sin^2\theta_{23}$, and Δm^2_{32} are considered
  - Nominal assumption: $\sin^2 2\theta_{13} = 0.1$, $\delta_{CP} = 0$, $\sin^2\theta_{23} = 0.5$, and $\Delta m^2_{32} = 2.4 \times 10^{-3}\mathrm{eV}^2$, normal MH
- Current T2K systematic errors used
  - $\sim$10% for ν_e, $\sim$13% for ν_μ
  - $\bar{\nu}$ errors estimated as equal to ν errors with an additional 10% normalization uncertainty
- With and without a reactor constraint based on the expected ultimate precision of Daya Bay + RENO + Double Chooz on $\sin^2 2\theta_{13}$ $(= 0.1 \pm 0.005)$

SK Reconstructed Energy Spectra at T2K Full Statistics (7.8×10^{21} POT)

ν_e Appearance ν_μ Disappearance

ν-Running

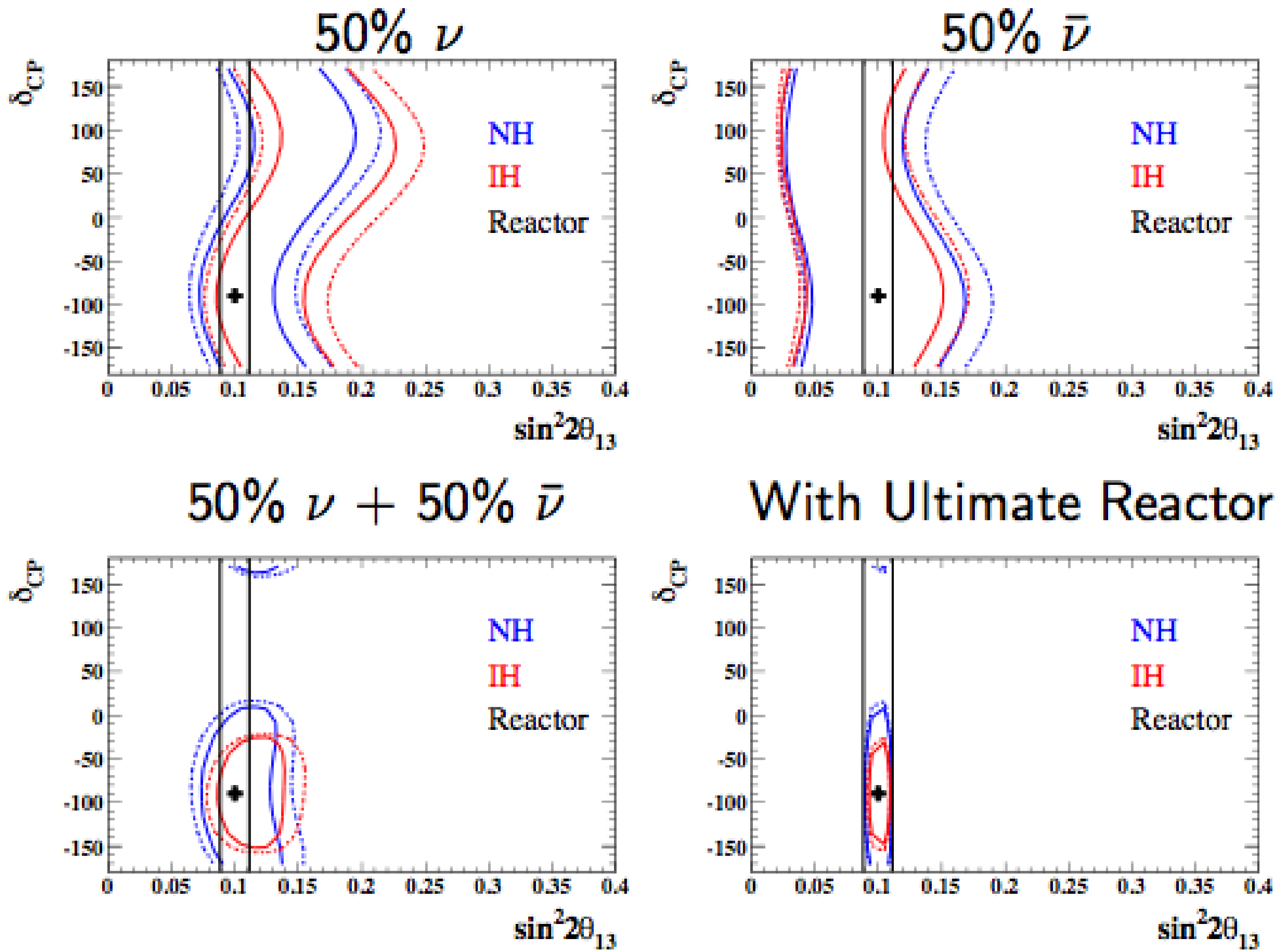
$\bar{\nu}$-Running



T2K 90% C.L. Regions for True $\delta_{CP} = -90°$, $\sin^2 2\theta_{13} = 0.1$

Solid: no sys. err., Dashed: with current sys. err.

True MH is NH; contours drawn for two MH assumptions

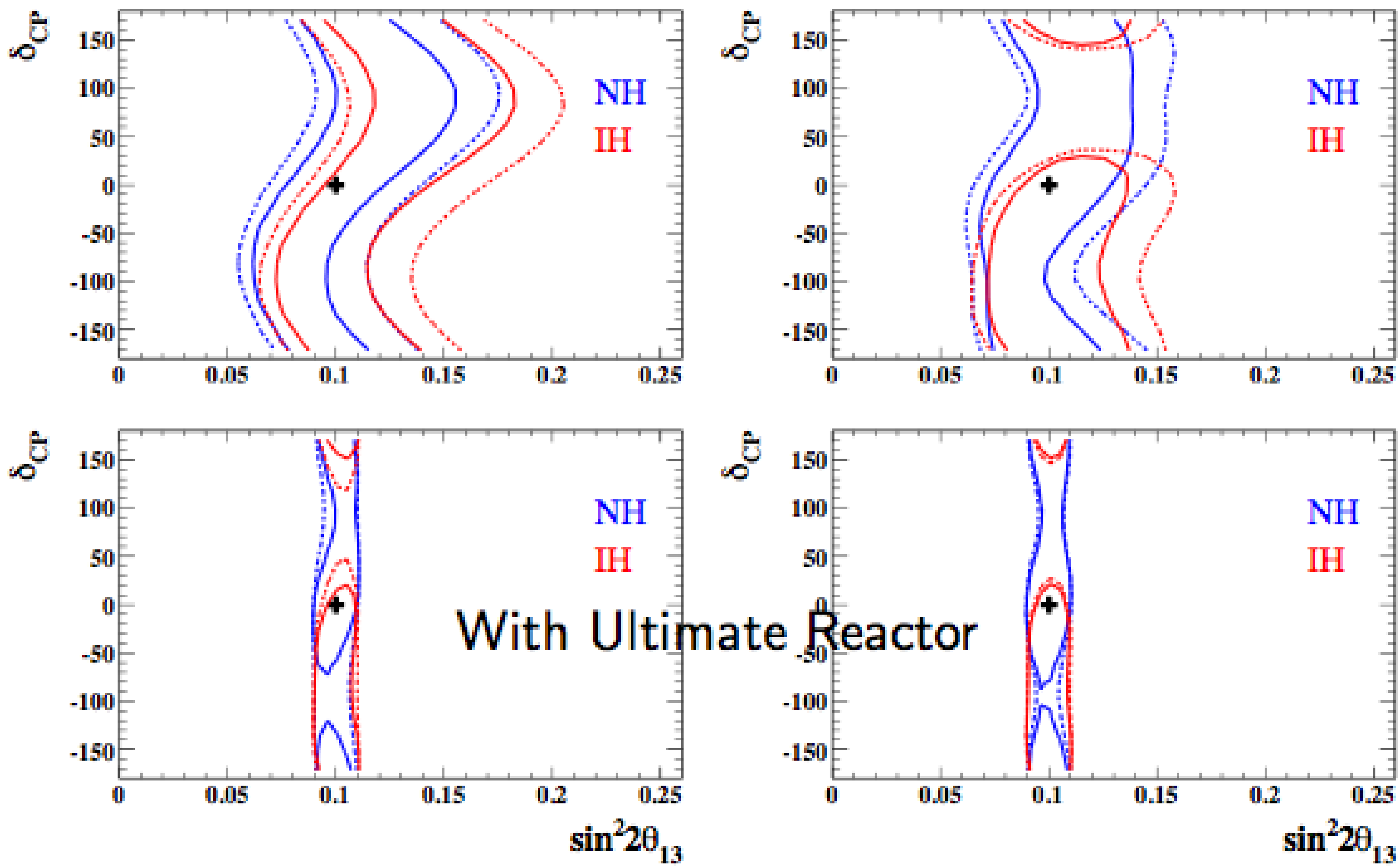


Ultimate T2K 90% C.L. Regions for True $\delta_{CP} = 0°, \sin^2 2\theta_{13} = 0.1$

Solid: no sys. err., Dashed: with current sys. err.

True MH is NH; contours drawn for two MH assumptions

100% ν | 50% ν, 50% $\bar{\nu}$



With Ultimate Reactor